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THE DISTRIBUTION OF HYDROGEN-ION CONCENTRATION IN THE NORTH-WESTERN INDIAN OCEAN AND ADJACENT WATERS

BY

A. F. MOHAMED, M.Sc., Ph.D.

(*Faculty of Science, the University, Cairo*)

WITH THIRTY-FOUR TEXT-FIGURES

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THE DISTRIBUTION OF HYDROGEN-ION CONCENTRATION IN THE NORTH-WESTERN INDIAN OCEAN AND ADJACENT WATERS

WITH AN APPENDIX ON THE DETERMINATION OF HYDROGEN SULPHIDE IN SEA-WATER WITHDRAWN FROM CERTAIN SAMPLES OF MUD COLLECTED FROM THE NORTH-WESTERN INDIAN OCEAN*

BY

A. F. MOHAMED, M.Sc., Ph.D.

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WITH THIRTY-FOUR TEXT-FIGURES.

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* It is not possible, in present circumstances, to publish the Tables of Data referred to in this Report; the Tables are preserved in the library of the British Museum (Nat. Hist.), where they are available for reference.

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INTRODUCTION.

A knowledge of hydrogen-ion concentration in sea-water is of prime importance in the study of the ocean. This quantity plays a governing rôle in the vital processes, conditions of existence and distribution of marine plants and animals. It provides the geochemist with valuable information in connection with the formation and re-solution of marine calcareous sediments. It may also prove, if accurately measured and properly corrected, of great aid to the oceanographer, at least from a qualitative point of view, in tracing the origin, history and movement of water masses.

The determination of hydrogen-ion concentration has been, in fact, one of the most attractive lines of the physical chemistry of the sea. In recent years attention has been turned to the study of the complex of physical and chemical factors—the so-called buffer mechanism—that determine and control the variation of hydrogen-ion concentration in sea-water (Henderson and Cohn, 1916; Buch, 1917; McClendon, 1917*a*; Schulz, 1921; Irving, 1925; Kreps, 1926; Saunders, 1926; Buch, 1930; Kändler, 1930; Thompson and Bonnar, 1931; Buch, Harvey, Wattenberg and Gripenberg, 1932; Gee, Moberg, Greenberg and Revelle, 1932; Buch, 1933; Wattenberg, 1933; Moberg, Greenberg, Revelle and Allen, 1934).

No attempt, however, is made in the present report to deal with this mechanism, since unfortunately not all the factors which are essential to its full discussion were experimentally determined. The experimental material on which this report has been based is limited to serial measurements of hydrogen-ion concentration.

The earliest quantitative contribution to our knowledge of hydrogen-ion concentration in sea-water was made by Ringer in 1908, whereas the first measurements over extended areas were made by Palitzsch in 1910 on the "Thor" (Palitzsch, 1912). Since then extensive observations have been made on the waters of several seas and oceans. These observations can be classified, for the purpose of surveying them, into three categories: (1) Observations made by expeditions, (2) observations made during more or less regular

cruises of vessels belonging to various countries—mainly to those who are members of the International Council for the Exploration of the Sea—and institutions, and (3) scattered observations by many investigators.

To the first category belong the observations made by the Danish Oceanographical Expedition on the " Thor " to the Mediterranean and adjoining seas in 1910 (Palitzsch, 1912); by the German Antarctic Expedition in the " Deutschland " in 1911–1912 (Brennecke, 1921); during the cruises of the "Armauer-Hansen" in the North-Eastern Atlantic in 1913 and 1914 (Helland-Hansen, 1914; Gaarder, 1927); by the Norwegian North Polar Expedition in the "Maud" in 1922–1924 (Sverdrup, 1929); by the German Atlantic Expedition in the " Meteor " in 1925–1927 (Wattenberg, 1933); by the " Discovery" in the South Atlantic in 1925–1927 ('"Discovery" Reports', Vol. I, 1929); by the Great Barrier Reef Expedition in 1928–1929 (Orr, 1933); by the " Discovery II " in the South Atlantic and in the South-Western Indian Ocean ('"Discovery" Reports', Vol. IV, 1932); by the "Nautilus" Expedition in the high latitudes of the North Atlantic in 1931 (Sverdrup, 1933).

The observations belonging to the second category are mainly published in the ' Bulletin Hydrographique ', 1921–1934. To this category belong the observations made by Finland in the Gulf of Finland and the Baltic in 1926–1934; by Norway in the Atlantic, Davis Strait, etc., 1924, in several fjords in 1928 (M.S. " Johan Hjort ") and in the North Sea and the Atlantic in 1929–1933 (M.S. " Johan Hjort "), and 1934 (M.S. "Armauer-Hansen "); by Denmark in the Cattegat, Belts, Baltic and Sound, in 1923 in the North Sea, Cattegat, etc., and the Atlantic in 1925–1926, and in the Atlantic in 1928 (" Godthaab "), and 1931 (" Dana "); by Germany in the Baltic in 1926, 1929, 1931 and 1933 (" Poseidon "); by England in the North Sea in 1921; by Scotland in the North Sea in 1932 (H.M.S. " Challenger " and " Explorer "); by Lithuania in the Baltic in 1934 (S.S. " Hidrografs "); by Portugal off the Portugal coast in 1934 (S.S. "Albacora "), by Japan in the Japanese waters in the Pacific in 1930–1935 (R.M.S. " Syunpu Maru " and the Training-ship " Skintoku Maru "); by Woods Hole Station of U.S.A. in the Atlantic in 1932–1934 (M.Y. "Atlantis "); by the State Oceanographical Institute of U.S.S.R. in the Barents Sea in 1927–1930 (Brujewicz, 1931).

To the third category of observations belong those made by Ringer (1908) on the waters of the Zuider Zee, North Sea and Bømmel Fjord; by Buch (1914) on the waters of Pojowiek; by Moore, Prideaux and Herdman (1915) on the Irish Sea waters; by Nansen (1915) on the Spitzbergen waters; by McClendon (1917*b*) on Tortugas waters; by Gaarder (1917) on the waters off the Norwegian coast and fjords; by Buch (1917) on the waters of the Gulf of Finland and the Baltic; by McClendon (1917) on waters from San Diego and waters from the Gulf Stream off Miami and Florida; by Mayer (1917) on the surface waters of the tropical Pacific; by Gail (1919) on the waters in the region of the Puget Sound; by Mayer (1919) on the waters of the Pacific from Fiji to Honolulu, Samoa, and San Francisco; by Crozier (1920) on the water in the lagoons at Bermuda; by Powers (1920) on the Pacific waters; by Michael (1921) on the waters off the coast of southern California; by Atkins (1922) on the sea-water off Plymouth Sound and the adjacent parts of the English Channel; by Cameron and Mounce (1922) on the waters in the Strait of Georgia and adjacent waters; by Labbé (1922) on the waters at Croisic and Batz; by Legendre (1922) on the water at Concarneau; by Mayer (1922) on the tropical waters of the Atlantic and Pacific; by Schulz (1922) on the North Sea and the Baltic Sea

waters ; by Atkins (1923) on the English Channel waters ; by Legendre (1923) on the Concarneau waters ; by Schultz (1923) on the Baltic waters ; by Allee (1923) on the waters in the vicinity of Woods Hole ; by Legendre (1924) on the waters in the Bay of Concarneau ; by Bruce (1925) on the waters of Port Erin Bay ; by Atkins (1926) on the English Channel waters ; by Kreps (1926) on the waters from Kola Fjord in the Arctic ; by Moberg (1926) on the waters off the coast of the southern California ; by Marshall and Orr (1927) on the waters in the Clyde Sea area ; by Ito (1928) on the water in the south-western portion of the north Pacific ; by Moberg (1928) on the sea-water off the coast of southern California by Seiwell (1928) on the surface waters of the English Channel and the southern North Sea ; by Bini on the waters of the southern Red Sea (1929) ; by Johnson and Thompson (1929) on the sea-water at the Puget Sound Biological Station ; by Thompson, Miller, Hitching and Todd (1929) on the Puget Sound waters ; by Reiss and Vellinger (1929) on the sea-water in the vicinity of Tunis ; by Wimpenny (1930) on the Suez Canal water ; by Schulz (1931) on the surface waters between Iceland and Greenland ; by Seiwell (1931) on the waters of the North Sea, the southern entrance to the Norwegian Sea and the water south of Iceland ; by Zanco (1931) on the Calgiari waters ; by Kreps and Verjbinskaya (1932) on the waters of the Barents Sea ; by Marchand (1932) on the waters in the vicinity of the Cape Point ; by Zanco (1932) on the waters at Calgiari ; by Cooper (1933*a*, *b*) on the waters of the English Channel ; by Miller (1934) on the surface waters between Hong-Kong and England by way of the Cape of Good Hope, including observations in the Indian Ocean between Colombo and Mombasa.*

From the foregoing survey it will be seen that, with the exception of the few surface observations made by Miller on the surface waters between Colombo and Mombasa, no systematic measurements of hydrogen-ion concentration have been made on the waters of the north-western Indian Ocean prior to the John Murray Expedition in 1933–1934.

In the present report it is therefore intended to record, describe and discuss the distribution of hydrogen-ion concentration values observed by the John Murray Expedition in H.E.M.S. " Mabahiss " in the Indian Ocean.

To express the magnitude of hydrogen-ion concentration more simply, Sørensen (1909) proposed that instead of the numerical value itself, its common logarithm with the negative sign omitted should be employed, and he called this figure the hydrogen-ion exponent, pH. Throughout this report this mode of expressing the hydrogen-ion concentration will be followed.

AREA OF INVESTIGATION.

The observations recorded in this report were made during the following cruises of H.E.M.S. " Mabahiss " into the Indian Ocean in 1933–1934 :

Cruise.	Stations.	Dates.
1. Red Sea to Aden	7–9, 12–14, 17	September 9th to 22nd, 1933.
2. Aden to Aden	19–23, 25, 32	September 28th to October 17th, 1933.
3. Aden to Karachi	38–41, 43, 46, 47, 49–52, 60	October 21st to November 10th, 1933.

* This survey, which covers observations published until 1934, is by no means complete and merely serves as a guide to more detailed information as well as to geographical distribution of observations.

Cruise.	Stations.	Dates.
4. Karachi to Bombay.	76, 81–83	November 17th to December 8th, 1933.
5. Bombay to Mombasa	91–93, 95, 97, 101, 102	December 13th to 31st, 1933.
6. Mombasa to Zanzibar.	116–118	January 9th to 24th, 1934.
7. Zanzibar to Colombo	127–134	January 30th to February 22nd, 1934.
8. Colombo to Colombo	136, 145	March 17th to April 13th, 1934.
9. Colombo to Aden	166, 167, 169–171, 173–175, 181, 183, 187, 195	April 19th to May 8th, 1934.
10. Aden to Red Sea	197–204, 206, 208	May 14th to 21st, 1934.

Text-fig. 1 shows the positions of the various sections and the locations of the stations at which pH observations were made. The sections are denoted by letters and the stations by numbers, which are to be found in the List of Stations (Sewell, 1935), where information regarding position, date, time, depth, meteorological conditions, etc. can be found.

METHOD.

For the measurement of pH of sea-water on board the " Mabahiss " the colorimetric method was used. Accurate measurements of pH by this method dates from the pioneer work of Sørensen (1909). The method was developed for hydrographic investigations by Sørensen and Palitzsch (1910).

The principle of the method consists in adding to a measured sample of sea-water, whose pH is to be determined, a measured volume of a suitable indicator and comparing the colour so produced with that of the same indicator in standard solutions of known pH. These pH-known solutions, or " standard reference solutions " as they are called, are buffer mixtures prepared by mixing two buffer solutions in certain proportions and determining their pH electrometrically. The colorimetric method is therefore a comparative one, and its accuracy depends primarily on the accuracy of the electrometric method, which is assumed to give correct and absolute results.*

Under the various sub-headings in this section the technique employed in preparing the buffer solutions, indicators and standard reference solutions and in measuring the pH of sea-water samples will be described ; the effects of salts, temperature and pressure on the colorimetric determination of pH will also be discussed.

Buffer Solutions.

McClendon borax-boric acid buffer mixtures (McClendon, 1917*a*) were employed. Two stock buffer solutions of borax (28·67 grm. of borax + 22·50 grm. of sodium chloride per litre) and boric acid (18·60 grm. of boric acid + 22·50 grm. of sodium chloride per litre) were prepared from Analar chemicals which received no further purification. The

* Brönsted and Grove (1930) stated, however, that the electrometric method cannot be considered as the most reliable method for accurate determinations of hydrogen-ion concentration since measurements by this method are considerably affected by salts.

water used in preparing these solutions was twice re-distilled, boiled to remove dissolved carbon dioxide and finally cooled in a tightly-stoppered flask. As soon as each solution was prepared it was introduced into a waxed bottle which had been fitted with a soda-lime tube and filled with CO_2—free air. Each bottle was connected with a 10 c.c. burette reading to 0·05 c.c. Both burettes were also fitted with soda-lime tubes.

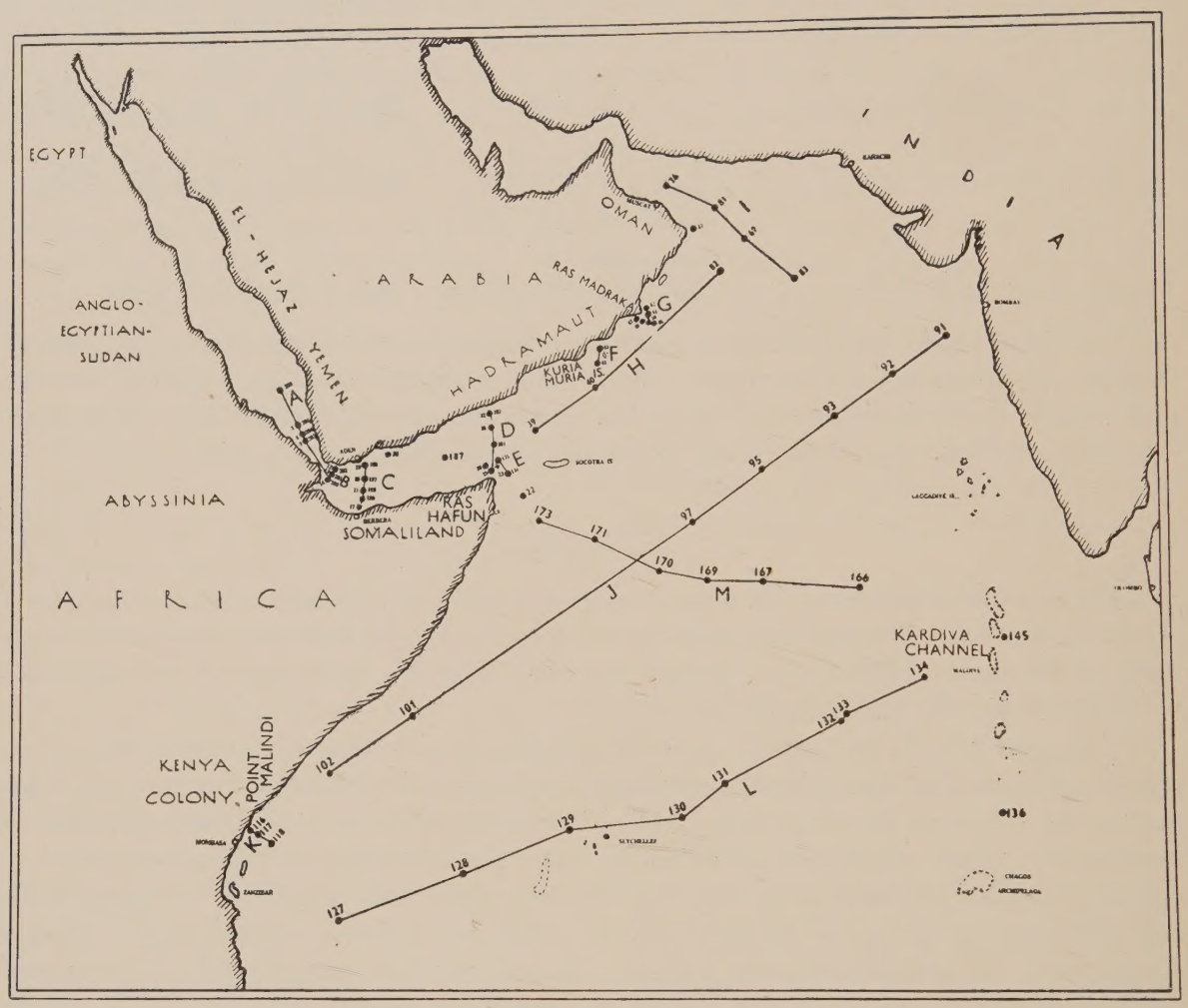

FIG. 1.—SHOWING THE POSITIONS OF STATIONS AT WHICH pH OBSERVATIONS WERE MADE

Indicators.

Three indicators were used, namely, cresol red, thymol blue, and phenol red. For preparing indicator solutions Clark's method (Clark, 1928) was employed. This consists in dissolving the indicator in the theoretical amount of base necessary to form the salt, and then diluting with water to the required concentration. This method of preparing aqueous solutions of indicators was used in preference to other methods in which alcohol is used as a solvent, since it was anticipated that in the tropical regions it would be very difficult to prevent completely the alcoholic solution becoming concentrated by evaporation while in actual use.

The following stock solutions of indicators were prepared: 0·2% cresol red, 0·2% phenol red, and 0·4% thymol blue. These stock solutions were stored in well-stoppered

waxed bottles. From these solutions the more dilute concentrations, 0·02%, 0·02%, and 0·04% respectively, used in the actual pH measurements were prepared as needed.

Standard Reference Solutions.

Thin monax test-tubes were chosen to contain the standard reference solutions. The tubes were cleaned with chromic acid mixture, distilled water and then steamed for a considerable time. They were left to drain and were finally dried in an air oven at 110° C. The tubes were carefully graded, and only those having the same bore were used. Each tube was then constricted near the top to a narrow neck, filled with buffer solutions in correct proportions as given by McClendon (1917*a*) and quickly sealed so as to avoid CO_2 getting in. The total volume of buffer mixture in each standard tube was 10 c.c. against 30 c.c. used by McClendon. The procedure followed in filling each tube was first to place in it one drop of purified toluene, the indicator solution (0·5 c.c.), the borax solution, and finally the boric acid solution. Toluene was added to obviate the action of glass and to prevent the growth of moulds, so that the pH would not alter on keeping (Atkins, 1922). The tubes were labelled so as to give valid readings when used for measuring the pH of sea-water with a salinity of *ca.* 33°/$_{oo}$.* The pH interval between the consecutive tubes of the scale was 0·02 unit.

Three sets of buffer standards were prepared ; each set was contained in a specially-made wooden box. The range covered by each set was from pH = 7·00 to pH = 8·80 ; and the range of use of each indicator was as follows: Phenol red, 7·00–8·10; cresol red, 7·50–8·40 ; thymol blue, 8·20–8·80. The tubes were kept in the dark when not in use, in order to avoid the bleaching action of light. Only one set of buffer standards was used on the present Expedition, and it was checked now and again against one or the other of the two additional sets, which were kept all the time unexposed to light. No fading was detected during the period of nine months.

Samples of Sea-water for pH Determination.

When taking the sea-water samples for pH determination the sample bottle was almost completely filled, a small or no air space being left over the water. As a rule the pH was determined on the day of collection or occasionally on the following morning, in which case the samples were preserved on collection with one drop of a saturated solution of mercuric chloride to stop the activity of micro-organisms. It was shown by Ibanez (1931) that under these conditions there was little or no change in the CO_2 content of the sample.

Measuring the pH of the Sea-water Sample.

Ten c.c. of the sea-water sample were added to 0·5 c.c. of the indicator solution which had been measured into a test-tube of equal bore to the tubes of the standard set. The colour comparison with the standard tubes was then made by the eye, usually under diffused daylight against a white background, but occasionally under artificial light. When the matching of the sample and the standard was completed, the pH value marked

* This validity was assumed in the belief that the salt-error corrections found by McClendon were accurate. Czyhirin (1931) has, however, shown, as will be described later, that these corrections were misleading. These readings became therefore subject to further corrections.

on the latter, as well as the temperature of measurement, was recorded. With practice it was possible to make the colorimetric determination in a few seconds.

Cresol red was found to be the most useful indicator which satisfactorily covers the whole range of pH met with in the north-western Indian Ocean. Thymol blue was used for confirmatory determination over the more alkaline range, and phenol red over the less alkaline range.

The Effect of Sea-salt on the Colorimetric Measurement of pH.

It is well known that the colorimetric method of measuring hydrogen-ion concentration is subject to certain errors, which should be corrected if results identical with those of the electrometric method are to be obtained. In his fundamental work Sørensen was aware of the effect of salts on the colours of indicators, and Sørensen and Palitzsch (1913) determined the salt-error corrections for several indicators. Their method of determining the salt-error of an indicator in sea-water consisted in acidifying the sea-water and passing hydrogen through to displace carbon dioxide, then neutralizing the sea-water to the range of the indicator under examination with buffer mixture, and finally comparing the colorimetric with the electrometric measurements. Commenting on this method of determining the salt-error, Clark (1928, p. 182) states that " such calibration is one of the very best ways to deal with the salt-error, since it tends to bring measurements to a common experimental system of reference ". Sørensen and Palitzsch's work was followed by that of several investigators, who made more or less detailed experimental study of the salt-errors of indicators (Wells, 1920 ; Kolthoff, 1922 ; Ramage and Miller, 1925 ; Czyhirin, 1931 ; Brujewicz and Skopintzew, 1933 ; Buch and Gustafsson, 1934 ; Mitchell and Taylor, 1935 ; Mitchell, Buch and Rakestraw, 1936). Because of the lack of uniformity in the methods used in the determination of the salt-error of the same indicator in sea-water, however, different salt-error corrections were applied to measurements of pH in sea-water.

This, added to the fact that various methods and buffer standards have been used in measurement of the pH of sea-water, makes the existing data tedious and difficult to compare. For instance, the discordance between pH values obtained by using Palitzsch buffer standards (Palitzsch, 1915) and those obtained by using McClendon buffer standards (McClendon, 1917*a*) after applying the salt-error correction conformable to each set of standards, was found to be striking (Czyhirin, 1931 ; Brujewicz and Skopintzew, 1933). Palitzsch's buffer standards have been in common use in marine investigations of pH. The fact that we have used McClendon's buffer standards on the " Mabahiss " makes this disagreement of a special interest to us and worthy of our consideration.

According to McClendon, his borax-boric acid buffer standards give correct readings (*i. e.* identical with electrometric measurements) when used for measuring the pH of sea-water which has a salinity of *ca.* $33^{\circ}/_{\circ\circ}$, and a slight salt-error correction has to be applied for other salinities. McClendon determined the salt-error of cresol red and thymol blue. His method differed, however, from Sørenson and Palitzsch's, which has been in general use, in that he used for his determinations samples of natural sea-water which had not been neutralized.

Recently Czyhirin (1931) made new determinations of the salt-error of cresol red in sea-water when McClendon buffer standards are used as a comparison scale. He employed the usual method of salt-error determination (Sørensen and Palitzsch, 1913). The

electrometric determination was carried out in a hydrogen electrode and the accuracy of both the electrometric and colorimetric determinations is claimed to be ± 0·01 pH.

From his determinations Czyhirin found a considerable divergence in the magnitude of the salt-error correction as determined by his own measurements and as given by McClendon. Czyhirin attributed this divergence to the fact that he used sea-water in which the carbonate buffer system was replaced by the borate system, as has been the case in the determination of nearly all known salt-errors, while McClendon used natural sea-water with a carbonate buffer system. Applying his salt-error corrections, determined for cresol red and McClendon buffer scale, Czyhirin obtained pH values identical with those obtained by the same indicator and Palitzsch buffer scale. The work of Czyhirin was later confirmed by Brujewicz and Skopintzew (1933).*

All our pH observations were corrected for the salt-effect by applying the corrections of Czyhirin (1931).

The Temperature Effect on the Colorimetric Measurement of pH.

The influence of temperature on the colorimetric determination of pH had been studied by only a few investigators (Walbaum, 1920 ; McClendon, 1917*a* ; Kolthoff and Bosch, 1927) before Buch published the results of his studies (Buch, 1929). From a systematic investigation of the influence of temperature on the dissociation constants of various indicators, when admixed with buffer mixtures and with sea-water, on the pH of buffer mixtures and on the pH of sea-water, Buch showed that the temperature plays a complex part in the colorimetric measurement of pH of sea-water, and that, in order to get accurate results, observations should be corrected for the temperature effect.

As a result of spectrophotometric measurements of the absorption of light by various indicators when admixed with buffer mixtures and with sea-water at varying temperatures, Buch proposed the following equation for the reduction of the observed pH values to the temperature of the water *in situ* :

$$pH_w = pH_b + a(t_b - t_w) + \beta\,(t'_w - t_w)$$

where pH_w = the pH of sea-water at its temperature *in situ*,

pH_b = the pH of the matching standard buffer tube reduced to the temperature of measurement,

t_b = the temperature of the standard buffer tube at the time of measurement,

t_w = the temperature of the sea-water *in situ*,

t'_w = the temperature of the sea-water sample at the time of measurement,

a = a constant, individual for each indicator, showing the amount by which the dissociation exponent of the indicator varies for a temperature change of one degree in borax-boric acid buffer mixtures,

and β = another constant indicating the colour change of the indicator which takes place in sea-water (S = 34·5°/$_{oo}$) with changing temperature.

Recently Brujewicz and Skopintzew (1933) reinvestigated the temperature effect on the colorimetric determination of pH in sea-water, and as a result of their investigation

* It is interesting to note here that Miller (1934) pointed out that the pH values which he observed in the English Channel agreed with the findings of Seiwell (1928), but were lower than the values observed by Atkins (1922). Similarly, the values observed by Miller (1934) in the tropical regions of the Atlantic and Pacific Oceans were in general lower than those found by Mayer (1922). Both Atkins and Mayer used McClendon's buffer standards and applied McClendon's smaller salt-error corrections.

they proposed an equation which resembles in form that of Buch. Their equation is as follows :

$$pH_w = pH_b + a\,(t_b - t'_w) - \gamma\,(t'_w - t_w)$$

where pH_w, pH_b, t_b, t_w, t'_w and a have the same indications as in Buch's equation, and γ is the temperature coefficient of the real (not the visual) change of pH of sea-water.

Both equations give practically concordant results. Brujewicz and Skopintzew's equation was, however, employed in correcting our observations for the temperature effect, since the data of these authors furnish values of the constants of the above equation for each of the three indicators, which we used, at different pH values.*

The first step in computing pH_w was to find out pH_b, the real pH of the matching standard buffer tube at the temperature of measurement. Brujewicz and Karpova (1933) investigated the temperature coefficient of the pH changes in Palitzsch borax-boric acid buffer mixtures and gave a table showing by how many pH units the inscription on the standard buffer tube, referring to a temperature of 18° C., would need to be corrected in order to give the real pH of the buffer tube at the actual temperature of measurement, *i. e.* pH_b. This correction is occasionally referred to in the literature as the Walbaum correction (Cooper, 1933*a*). Since, however, the calibration temperature of McClendon buffer mixtures, which we used, was 20° C., and as one has good reason to assume that the sensitiveness of McClendon borax-boric acid buffer mixtures would be very similar to that of Palitzsch buffer mixtures, the table given by Brujewicz and Karpova was reconstructed so as to refer to a calibration temperature of 20° C. instead of to that of 18° C.

All the observed values of pH were then corrected for the temperature effect, using the equation of Brujewicz and Skopintzew, and in this way values of pH_w were obtained.

The Effect of Pressure on pH.

It is well known that the hydrogen-ion concentration in a sea-water sample is interrelated to its carbonic acid equilibrium. When a sea-water sample is brought up to the surface from a great depth its carbonic acid equilibrium is displaced as the pressure is diminished, and the volume of the sample is consequently increased. Buch and Gripenberg (1932), who investigated the effect of pressure on this equilibrium, give a table showing the magnitude of Δ pH to be subtracted from the pH value measured at the surface for an increase of depth of 1000 m. That table shows that the change in pH with depth is considerable, and that the difference, Δ pH, between pH at the surface and pH at a given depth, varies with pH.

If the present observations were further corrected for the pressure effect they would give the actual pH of the water *in situ*. But since the primary aim has been to present the observations in a form comparable with other modern data of pH, which are corrected only for salt and temperature effects, the correction for the pressure effect has not been made. This effect can be easily corrected by the use of Buch and Gripenberg's table. Further, I have based the description and discussion of the pH distributions not on the pH of the water *in situ*, but on the pH which the water would attain when raised to the surface, *i. e.* on the pH of the water at its temperature *in situ* but under atmospheric pressure. Presented in such a form (which is analogous to the " potential temperature "

* More recently Buch (1937) himself has recommended the use of Brujewicz and Skopintzew's equation for the correction of the temperature effect on the colorimetric measurements of pH.

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—an important notion introduced into oceanography by Helland-Hansen), the pH observations afford a means for following the movement of an individual mass of water, for it remains practically constant (if mixing, photosynthetic and geochemical processes be excluded), whereas the pH *in situ* would change as soon as the water mass moves to a different level.

Order in which Corrections have been applied and Presentation of Data.

In determining the constants of their equation for the temperature effect on the colorimetric measurements of pH, Brujewicz and Skopintzew used pH values which were not corrected for the salt effect. Our observed values of pH were therefore corrected first for the temperature effect, and the values of pH_w so obtained were then corrected for the salt effect. In this way the pH of sea-water at its temperature *in situ*, corrected for salt-error and measured under atmospheric pressure, was obtained. This value, which should be properly designated as pH_t, will be presented simply as pH in the text and in the Tables of pH Data (Column 3).*

The values of pH_w were also reduced to 0° C. and then corrected for the salt effect, and values of pH_o were thus obtained (Column 4). Reduction of pH observations to such a standard temperature as 0° C. would not only allow of comparison of pH observations amongst themselves (Cooper, 1933*a*), but also of an easy comparison with the observations of other investigators on the waters of the same region or of different regions, which is always highly desirable. Further, in order to allow our observations to be compared with other observations, which had been corrected only for the salt effect and recorded in the literature, they have been similarly corrected for salt-error only and the corrected values are entered in the Tables of Data (Column 2).

Accuracy of Results.

As the interval between successive tubes in our buffer scale is 0·02 pH unit, our observations are accurate to ± 0·01 pH. They are in very close agreement with the observations made by Miller (1934) in the same area. The average pH of 13 surface observations which he made between Colombo and Mombasa is 8·13, measured at an average temperature of 26·6° C.; the average pH of 15 surface observations which we made between Mombasa and Colombo is 8·12, measured at an average temperature of 29·6° C. Both sets of observations were corrected for salt-error. Miller's measurements were made by a different colorimetric method with a different salt-error and were checked electrometrically. Our observations on the surface waters near the equator are also in close agreement with similar observations made by the "Meteor" in the tropical Atlantic regions. We must, however, bear in mind that colorimetric measurements are subject to certain errors, such as those due to eye-strain, non-uniformity of light, etc. We have therefore checked all our observations graphically, station by station, and, in certain doubtful cases, mutually with corresponding hydrographic data. This process rendered 1–2% of the total number of observations most probably incorrect and they were discarded. Missing values were found by graphical interpolation.

As to the absolute value of our observations the following general remarks on

* These Tables of Data are preserved in the Library of the British Museum (Nat. Hist.), where they are available for reference.

measurements of pH may help to show how far or near these measurements are from absolute correctness.

There is much confusion in the literature regarding the real significance of pH. When Sørensen carried out his work on the determination of hydrogen-ion concentration, the modern theory of strong electrolytes had not been developed, and, of course, his measurement and calculation of hydrogen-ion concentration were based on the classical theory of Arrhenius (1899), which postulated incomplete dissociation of strong electrolytes in aqueous solutions. According to the modern theory, dilute aqueous solutions of strong electrolytes are completely dissociated into ions and the results arrived at by conductivity determinations and by osmotic or electrometric measurements, which have been interpreted as indicating incomplete dissociation of the electrolyte, have their natural explanation when the interionic forces acting between the electrically-charged ions are taken into consideration.

Owing to these interionic forces, the active mass of an ion, its activity (a), cannot be taken as equal to its concentration C, the proper equation for these quantities being :

$$a = f_a \, . \, C$$

where f_a, termed the activity coefficient, differs for the different ions, and varies for the individual ion with the nature and concentration of the other ions present. In the light of this conception a distinction should be made between the total hydrogen-ion concentration and the activity of hydrogen ions. For instance, the concentration of hydrogen ions in 0·01 NHCl is equal to the total concentration of the acid, hence $[\dot{H}] = 0{\cdot}01$. The activity of hydrogen ions is smaller and equal to $f_{\dot{H}} \times 0{\cdot}01$ where $f_{\dot{H}}$ represents the activity coefficient of hydrogen ions in 0·01 NHCl. We may represent this activity by $[a\dot{H}]$. Similarly we can represent the negative logarithm of hydrogen-ion concentration and its activity by pH and paH respectively.

Now in electrometric measurements it is the activity of hydrogen ions which determines the potential and it is actually the paH which is derived from these measurements. Since Sørensen computed his pH values (also pH values of buffer mixtures in common use) on the basis of the classical dissociation theory, whereas the new computations are based on the modern theory of strong electrolytes, it is obvious that the original notation of hydrogen-ion concentration (Sørensen pH) has no real meaning.

To clear up this confusion Kolthoff (1930) has proposed to assign to $[\dot{H}]$ and pH the significance they have according to the modern theory of strong electrolytes, and to express the corresponding activity and activity exponent by $[a\dot{H}]$ and paH. Values obtained on the basis of Sørensen's original work should be indicated by the Sørensen value $[s\dot{H}]$ and the Sørensen exponent by psH.

However, as most of the work which has been done in the past on the determination of hydrogen-ion concentration (hydrogen-ion concentrations of buffer mixtures, etc.) is expressed in Sørensen units, it seems better, mainly to avoid confusion, to adhere to them, though they have no actual significance. As soon as the difference between Sørensen psH and paH is fixed by international agreement it would be easy to transfer all psH values into paH.

It should therefore be understood that the pH values recorded in this report are really Sørensen values (psH), in spite of the fact that they are expressed as pH for simplicity. It would be a wide step in chemical oceanography if one rule could be observed in calculating and in publishing the hydrogen-ion measurements.

DISTRIBUTION.

The distribution of hydrogen-ion concentration in the north-western Indian Ocean and its adjoining gulfs will be dealt with under the following headings :

(1) Vertical distribution,
(2) Horizontal distribution,
(3) Discussion of distributions,

with reference to the origins and relationships of the different water masses.

Both description and discussion of distributions will be based on the value which the pH *in situ* would attain when the water sample is raised to the surface. As already mentioned in a previous section, this value is simply referred to in the text as pH and not as pH_t.

Vertical Distribution.

In vertical section we recognize in the distribution of pH in the north-western Indian Ocean a general fundamental type valid for the entire area of investigation. In certain regions this type may, however, be modified into subordinate types by local conditions, currents, or seasonal changes.

The outstanding features of this general type are as follows. Throughout the north-western Indian Ocean the highest values of pH occur, as a rule, in the more or less homogeneous surface waters overlying the thermocline. With increasing depth the pH decreases until it reaches a minimum value in mid-depths. The depth at which the minimum value of pH occurs varies from one region to another, and in certain regions it varies with the season. With further increase of depth there is a constant, sharp or gradual, increase in pH until it reaches a relatively high value at the greatest depth sampled. However, over the southern end of the Red Sea, in the Gulf of Aden and its approaches, and in the Gulf of Oman the occurrence of secondary maxima and minima is not unusual, though less frequent in the open ocean.

These general features are illustrated by a series of selected pH-depth curves (Text-fig. 2).

The highest surface pH value met with in our area of investigation (pH = 8·16) occurs at Station 93, in the central Arabian Sea, and the lowest surface pH value (pH = 7·91) occurs at Station 49, off Ras Madraka on the South Arabian coast. The usual range of surface pH is, however, 8·02–8·13.

The minimum value of pH occurring at mid-depths (pH = 7·56) is found at Station 12, which lies on the northern side of the Gulf of Aden at its western end. The usual range of minimum pH values is, however, 7·66–7·80.

The highest pH value occurring at great depths (pH = 8·18) is found at a depth of 4000 m. at Station 167.

As the upper limit of the range of minimum pH values is in general 7·80, and in order to bring to light the regional differences of vertical distribution, the whole water column in a vertical profile will be divided, for convenience of description, into three main pH layers—an upper layer with higher values of pH, a mid-layer with low values, and a lower layer with relatively high values of pH as defined by the position of the 7·80 isolines. At stations where there are more than two 7·80 isolines in a vertical profile, the division of

the water column into layers will be modified accordingly. It should be borne in mind, however, that in the actual description of a vertical profile the pH vertical gradient—which, for convenience, will be defined as the number of pH units per 100 m. difference of depth—at any part of the water column will be taken into consideration as well. Thus, the lower boundary of the surface layer will be taken as the level at which the pH vertical gradient is greatest in the upper part of the water column.

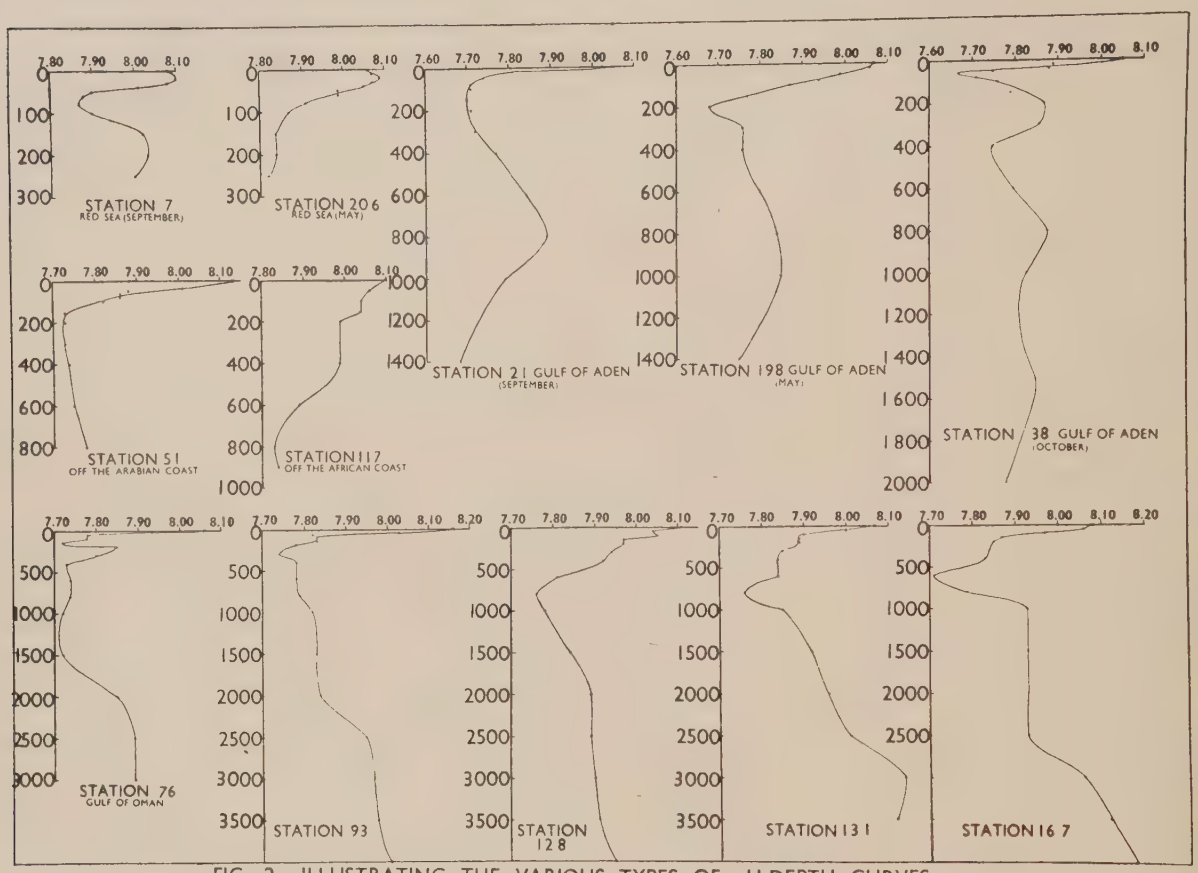

FIG. 2.—ILLUSTRATING THE VARIOUS TYPES OF pH-DEPTH CURVES.

Vertical profiles.—The vertical profiles of pH in all sections (Sections A–M) along the southern end of the Red Sea, across the Gulf of Aden, in the Gulf of Oman, in the Arabian Sea and the north-western Indian Ocean are shown in detail in Text-figs. 3–22. The profiles make no allowance for the fact that owing to stress of weather and currents the stations did not fall always along a straight line. The bottom relief is based on the topographical results of the present Expedition (Farquharson, 1936). The stations constituting a section are in all cases indicated by numbers above each profile. The isolines are drawn at intervals of only 0·05 pH in order to avoid the figures being crowded by lines, though the accuracy of our measurements is much greater.

The Southern End of the Red Sea.

Section A : Conditions at the end of the summer season (September) (Text-fig. 3).—Observations of pH were made at three stations (7, 8 and 9) along Section A in September. Over this southern end of the Red Sea the surface pH is high and uniform, as it varies only

from 8·08 to 8·10. Since the pH of sea-water is dependent upon the equilibrium conditions of the carbonic acid system, this high pH is obviously due to the phytoplanktonic activity

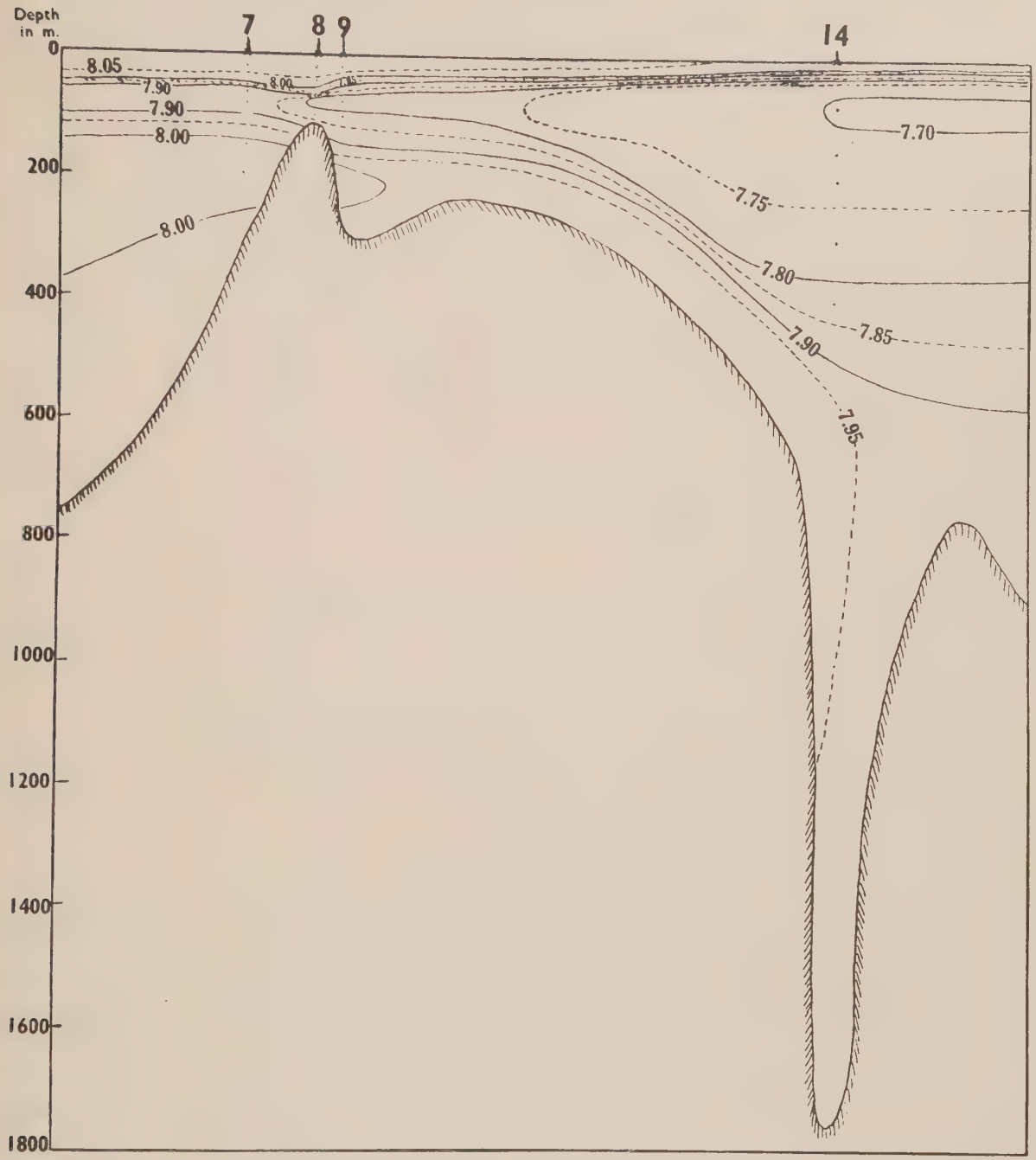

FIG. 3.—THE DISTRIBUTION OF pH ALONG SECTION A IN THE SOUTHERN END OF THE RED SEA AND THROUGH THE STRAITS OF BAB-EL-MANDEB (SEPTEMBER).

which reduces the carbon dioxide content of the surface waters, thus causing the pH to rise.

As is seen from the Tables of pH Data (Stations 7, 8 and 9) the maximum pH of the

surface waters does not occur usually at the surface, but at a depth of 20 m. This fact indicates that, in so far as the phytoplanktonic activity is reflected by pH vertical distribution, the maximum phytoplanktonic activity does not necessarily take place at the very surface of the sea, but just below it. A possible explanation of this is that the light is often too intense at the surface (Marshall and Orr, 1928), so that the zone of maximum phytoplanktonic activity lies well below the surface.

Descending below the surface, the pH remains constant or changes slightly until a depth of 30 m. is reached, below which it drops rapidly with increasing depth, until it reaches a minimum value at a depth of 80 m. This minimum value varies from 7·87 at the northerly station to 7·78 at the southerly one. This rapid decrease in pH will shortly be shown to be due to the influence of an inflowing current from the Gulf of Aden characterized by low pH values. Below the depth of minimum value the pH rises with increase of depth until it attains a secondary maximum value (8·02–8·03) at a depth of 200 m. Below this depth the pH falls to a value of 8·00 in the vicinity of the bottom. At Station 8, which is the shallowest on the section, the pH attains, however, a value of only 7·84 near the bottom, but such is the pH value characteristic of similar depths in the neighbourhood.

The greatest pH vertical gradient (pH units per 100 m. difference of depth) amounts to 1·10 pH units and occurs at Station 7 between the depths of 40 and 50 m. and at Station 9 between the depths of 30 and 40 m.

The conditions along this section as a whole are graphically represented in Text-fig. 3 on the left-hand side. From a pH standpoint we can distinguish at least three water strata over the southern end of the Red Sea at the end of the summer season : An upper stratum with a high pH and extending from the surface down to a depth of about 60 m.; a mid-stratum with lower values of pH and exhibiting a minimum at a depth of 80 m.; and finally a lower stratum with relatively high values of pH which extends to the bottom. The course of pH isolines through the Straits of Bab-el-Mandeb throws abundant light on the origin and movement of these three water masses, which will be considered in the following section.

The water movements in the Straits of Bab-el-Mandeb at the end of the summer season (September).—Section A (Text-fig. 3) is extended to include Station 14, lying in the western end of the Gulf of Aden, in order to bring out the conditions in the Straits of Bab-el-Mandeb in September. At this time of the year the vertical profile shows clearly the inflow of a massive sub-surface current, characterized by low pH values (7·80 and less), from the Gulf of Aden into the Red Sea. This inflow serves as a compensation for the water loss from the Red Sea due to excessive evaporation during the summer months. It is also seen that this inflowing water mass constitutes the bulk of the water column in the Straits at the time of observation. As the maximum inflow probably sets in at a time later than that of maximum evaporation, it is reasonable to assume that the inflow reaches its greatest intensity in September. The minimum value of pH within this inflowing water mass is as low as 7·70 at Station 14 in the Gulf of Aden, but it rises to 7·79 over the sill near Great Hanish Island, and to 7·87 at Station 7. It is thus seen that the pH of this water mass increases as it passes through the Straits into the Red Sea, presumably through mixing with Red Sea water in the neighbourhood of the sill.

The deep layer with relatively high pH values is seen in the profile to flow as a bottom current out of the Red Sea. The curved course of the 8·00 isoline indicates that this

bottom current, after passing for a short distance over the sill, turns back into the Red Sea. Such a course is probably taken by the current in view of the combined resistance offered against it by the obstruction of the sill and the great volume of the inflowing current. It should, however, be noted that it is possible that this turning back of the Red Sea bottom current may not be a permanent feature and it is likely that this current is at times overcome by the ingoing tidal current. The water which succeeds in passing over the sill into the Gulf of Aden pours partly—owing to the sudden increase in depth at Station 14—into the deep gully, as shown by the course of the 7·95 isoline, which is seen in the profile to be filled with water having a relatively high pH, and partly runs, as shown by the course of the lower 7·90 isoline, into the general depths of the Gulf of Aden. Had we taken reliable pH observations north of Station 7 we might have been in a better position to trace the origin of this bottom water further north in the Red Sea.

The *régime* of surface currents in the Straits is determined mainly by the prevailing winds, but is influenced to a lesser degree by the tidal streams. At the time of observation the direction of the wind (N.N.W.–N.W.) was such that a wind-driven current flows out of the Red Sea into the Gulf of Aden. The course and trend of the isolines within the surface layer also bear out this impression, but it should be borne in mind that, though Mayer (1919) pointed out that surface currents could be detected from pH observations, on account of planktonic activity in the surface layer which ensues with different intensities at different times, conclusions regarding surface currents from pH observations should be made with great caution.

It is thus seen that the distribution of pH in the Straits of Bab-el-Mandeb in September is determined mainly by the *régime* of currents in the Straits at that time. Similar conclusions regarding the water movements in the Straits of Bab-el-Mandeb have been reached by Vercelli (1931) from the hydrographical observations and direct current measurements of the "Amiraglio Magnaghi" in July, 1929, and by Sewell (1934) in a preliminary treatment of the temperature and halogen-content observations of the present Expedition. This shows that from pH observations, which have been properly corrected and reduced, it has been possible to follow and trace the water movements in the Straits of Bab-el-Mandeb. The usefulness of pH observations in the study of such water movements is further borne out by the interesting fact that, when the average properties of the three water strata passing through the Straits are compared, the intermediate character of the mid-stratum shows itself in other properties, such as temperature, salinity and oxygen-content, as well as in pH.

Section A: Conditions at the end of the winter season (*May*).—Observations were repeated on the return journey during May along Section A at the same three stations of the summer season, the stations are now listed as 206, 204 and 203, and further observations were taken at Station 208, which lies north of Station 206.

At the end of the winter season the pH–depth curve in the southern end of the Red Sea presents a marked contrast to what it was at the end of the summer season in that it does not exhibit a minimum at mid depths, the minimum pH value occurring at the maximum depth samples (Text-fig. 2, Station 206).

The surface pH varies from 8·06 to 8·10 (see Tables of pH Data) and, as is better shown by comparing the value of pH_0, it tends to be now lower than it was in the previous season. The maximum pH occurs again almost always below the surface at a depth of 10–20 m., indicating that the maximum phytoplanktonic activity takes place, as in the previous

season, below the surface. The pH vertical gradient is, on the whole, smaller than it was at the end of the summer season.

The vertical distribution of pH along Section A, as a whole, is represented in Text-fig. 4 on the left-hand side. This profile gives now a different picture of pH distribution and a comparison with the summer profile shows that from a pH standpoint only two layers can be distinguished over the southern end of the Red Sea in May. The separating boundary between these two layers is marked by a distinct pH vertical gradient. The pH of the deep layer is now much lower (7·82–7·95) than it was in September (8·00–8·03), and that of the surface layer, as already pointed out, is also lower.

Seasonal changes.—The cause of these seasonal changes in pH over the southern end of the Red Sea should be sought in the change of hydrographic conditions from the one season to the other as well as, so far as the surface layer is involved, in the variation of the rate of biological activity. A comparison of hydrographic conditions of the surface waters in September and May shows that the surface temperature over the southern end of the Red Sea was about 4° C. lower in May than it had been in September. The lowered temperature of the surface waters in May tends to increase the capacity of the surface to absorb carbon dioxide from the atmosphere and probably to make the photosynthetic processes slower. Since the pH of sea-water is determined by the equilibrium conditions of the carbonic acid system, this combined effect of temperature accounts for the low pH of the surface in the winter season.

The low pH values of the deep layer and its homogeneity, as shown by its small and uniform pH vertical gradient, suggest that this water-mass has been formed, in accordance with one of the fundamental conceptions of oceanic circulation, at the surface somewhere during the winter months, and it is reasonable to presume that it has its origin further north in the Red Sea. The low temperature of the surface in the northern regions of the Red Sea during winter increases the density of the surface water and causes it to sink.

The distinct pH vertical gradients existing between the surface layer and the water below it are due to the fact that winter conditions are disappearing and that the heating of the surface waters has already begun, giving rise to the formation of the ill-defined but recognizable boundary surface.

The water movements in the Straits of Bab-el-Mandeb at the end of the winter season (May).—Section A has been drawn to include Station 200 at the western end of the Gulf of Aden and thus to bring out the conditions in the Straits of Bab-el-Mandeb in May (Text-fig. 4).

The vertical distribution of pH in the profile of this section reveals several interesting points regarding the water movements through the Straits of Bab-el-Mandeb in May. It is seen that Red Sea water from mid and great depths flows out as a deep current into the Gulf of Aden. In the Straits the greater part of the water column consists now of this Red Sea water. The course of the 7·83 isoline north of the sill indicates an upward movement of the Red Sea deep water as it approaches the sill. This upward movement of the current pushes its water over the sill into the Gulf of Aden. The course of the isolines south of the sill indicates the subsequent history of this current. The greater portion of it pours down into the deep gully lying in the position of Station 200 and at the same time flows further into the general depths of the Gulf, with a nucleus at about 500 m. This deep Red Sea current, characterized by its deep course and somewhat high pH values, will be traced further in the Gulf of Aden in describing Sections B, C and D.

The direction of the wind at the time of observation (E.–E.S.E.) was such that a surface wind-driven current would flow from the Gulf of Aden into the Red Sea, and the course of the 8·10 isoline also gives this impression.

We come, therefore, to the conclusion that in May there pass through the Straits of Bab-el-Mandeb a deep current which flows out of the Red Sea into the Gulf of Aden and

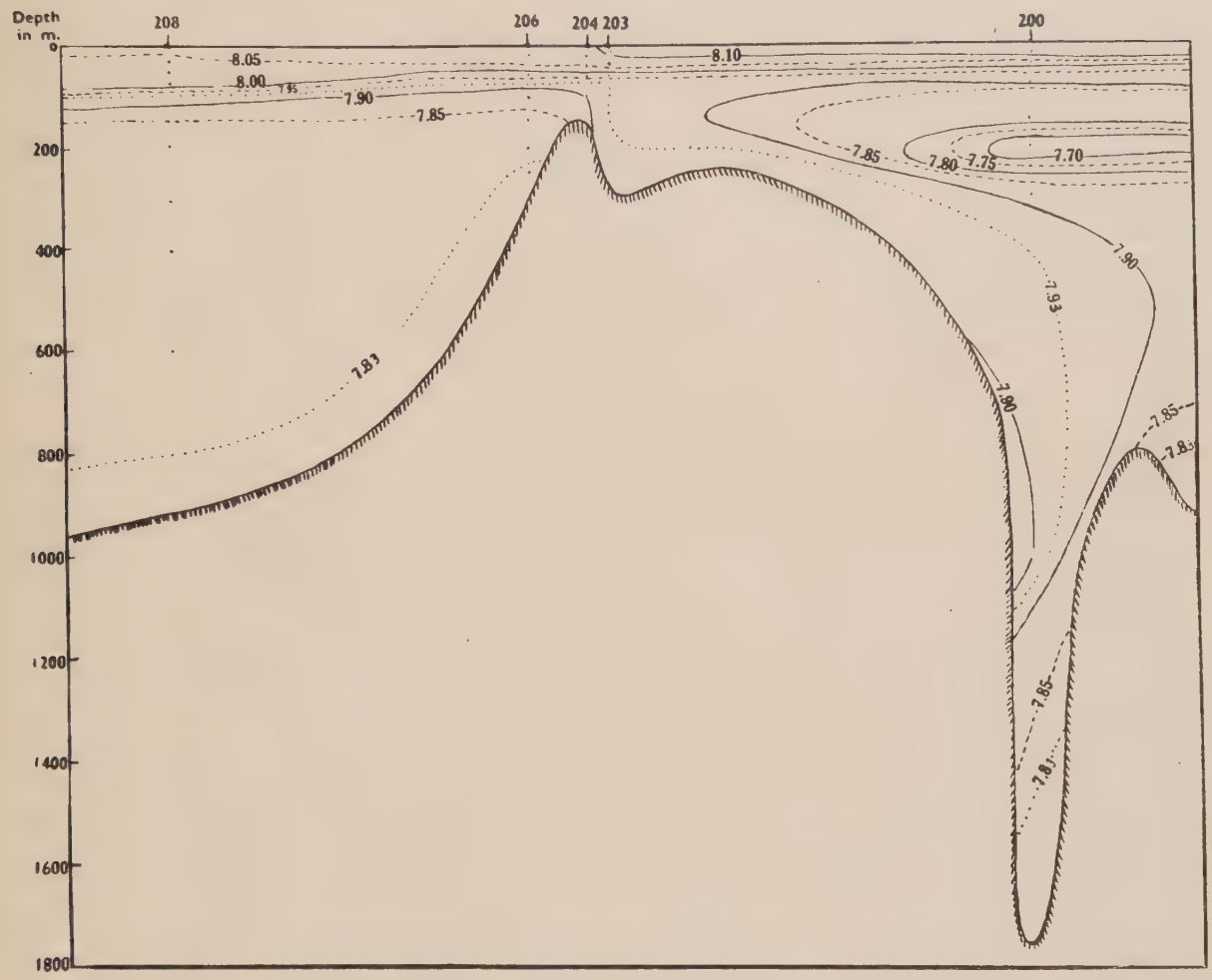

FIG. 4.—THE DISTRIBUTION OF pH ALONG SECTION A IN THE SOUTHERN END OF THE RED SEA AND THROUGH THE STRAITS OF BAB-EL-MANDEB (MAY).

constitutes the bulk of the water column in the Straits, and a surface current which flows into the Red Sea.

The much reduced sub-surface current, characterized by low pH values (7·80 and less), which was flowing into the Red Sea during September now hardly reaches the entrance of the Straits. It has even failed to drive back an upper band of the Red Sea deep current which eventually finds it way into the Gulf of Aden below the surface layer. The somewhat high pH value, which is higher than that of the surrounding water below and above it, found at a depth of 150 m. at Station 200, signifies the existence of this band of Red Sea water there. Owing to its small volume it is bound to lose its marked character before it travels far in the Gulf of Aden.

Before passing on to describe conditions along Section B, the interruption of the 7·90, 7·85 and 7·83 isolines at the sill calls for some comment. The interruption of the 7·90 isoline at the sill might be explained as due to vertical oscillations, which have been reported by Vercelli (1927) from this region and which result in thermo-haline oscillations, connected with the rhythm of the tide. However, to explain the interruption of the deeply situated 7·85 and 7·83 isolines on similar grounds seems inadequate, as it is hardly thinkable that vertical oscillations would extend to such great depths. This raises the question whether the deep water below 1000 m. in the gully has originated from Red Sea bottom water or from another source, presumably a mixture of mid and deep (not bottom) water from the Red Sea with another current, with low pH values, moving westwards along the bottom in the Gulf of Aden. In all probability the latter view seems sounder, and that is why the portions of the 7·85 and 7·83 isolines in the gully have been drawn to demonstrate this probability. This leads us to the conclusion that, pending the correctness of our view as to the origin of the water in the depths of the gully, the bottom water of the Red Sea is not involved to any great extent in the water-exchange through the Straits of Bab-el-Mandeb in May.

The Gulf of Aden and its Approaches.

Observations of pH along three sections B, C and D, running across the Gulf of Aden were made in September–October and were later repeated in May. Section B runs across the extreme western end of the Gulf, Section C runs between Aden and Berbera and Section D across the mouth of the Gulf at its eastern end. Observations along Section E, which runs through Socotra Channel were also made in October and were repeated in May. The pH distribution along each of these sections will be considered separately.

Section B: Conditions in September (Text-fig. 5).—Observations of pH along section B were made at three stations (12, 13 and 14) in September. Over this end of the Gulf the pH of the surface waters varies from 8·02 to 8·06. Below the surface the pH decreases suddenly to a minimum value of 7·56 at the shallow depth of 20 m. at Station 12, which lies on the Arabian side of the Gulf. This pH value is the lowest which we met in our area of investigation. At the other two stations on the section the minimum pH value amounts to 7·70 and occurs at lower levels. With increasing depth the pH increases till it reaches a value varying from 7·83 near the bottom in the northern side of the Gulf to 7·95–7·98 in the deep gully lying below Station 14.

The general arrangement of the water strata in the profile of this section is very similar to that found in the Straits of Bab-el-Mandeb in the month of September. One outstanding feature is the thickness of the layer with minimum values of pH (less than 7·80) which constitutes the greater part of the water column over the general depths of the Gulf. The cause of these low pH values within this layer must be sought in the hydrographic conditions at the time of observations. Examination of the temperature observations reveals at once the presence of a well-developed temperature gradient (and consequently a density gradient) near the surface along this section. The presence of such a sharp boundary between the layer under consideration and the surface layer prevents mixing across the boundary and makes the former dependent for its oxygen supply on lateral exchanges, thus leaving it in a state of relative stagnation. This layer becomes therefore a seat of organic oxidations, carbon dioxide being set free, and the pH is

consequently lowered. One fact, which strengthens this explanation is that the reduction in oxygen-content, as shown by the present Expedition data, stands in close correspondence

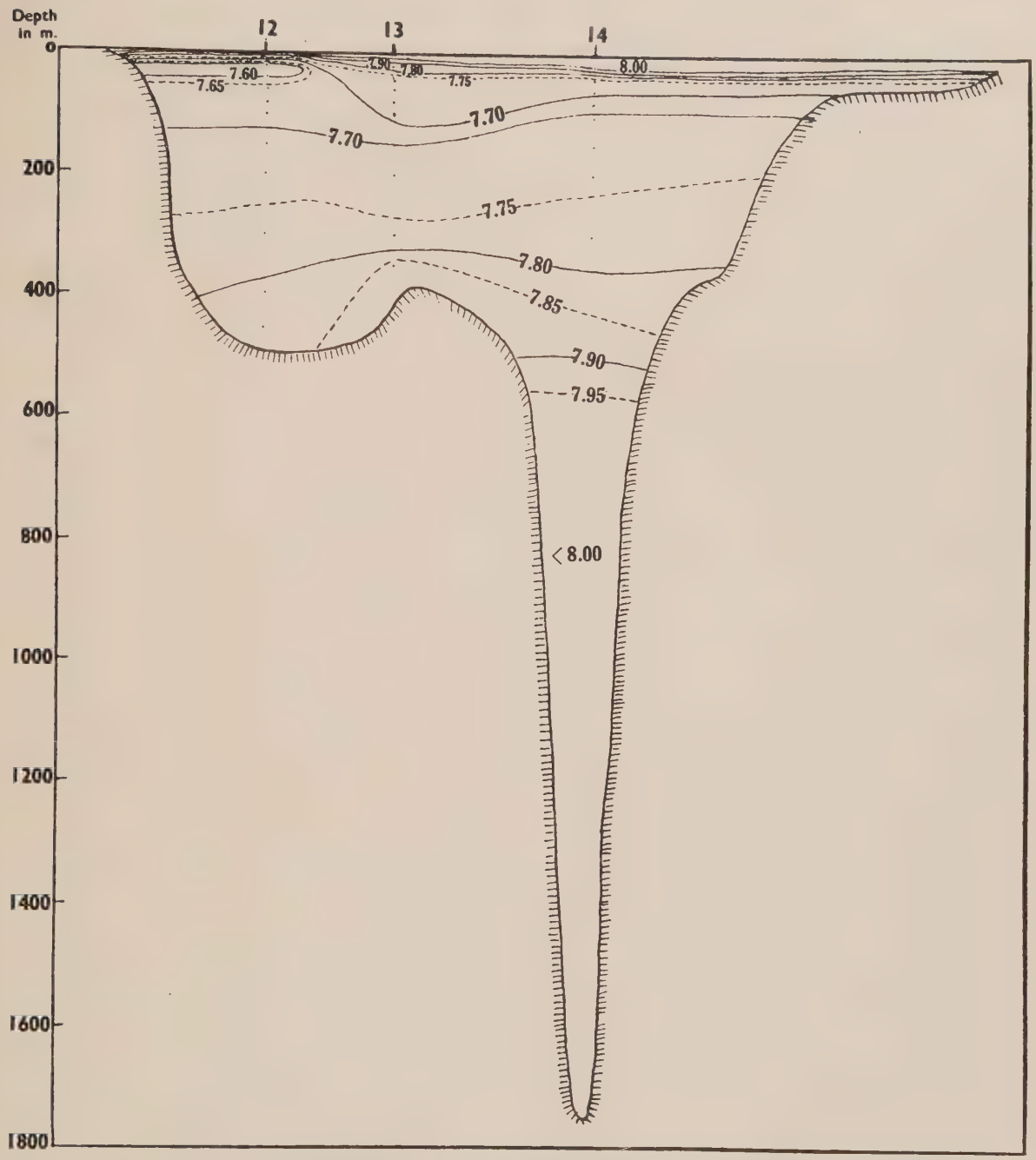

FIG. 5.—THE DISTRIBUTION OF pH ALONG SECTION B ACROSS THE WESTERN END OF THE GULF OF ADEN (SEPTEMBER).

with the decrease in pH. Moreover, the presence of a well-developed density gradient near the surface causes the decay of sinking organic *débris* (of similar specific gravity) to occur at a higher horizontal level and this results in an increase in the vertical thickness of the minimum pH layer. The upper and lower boundaries of this minimum pH layer

(upper and lower 7·80 isolines) give thus the approximate limits to which most of the organic oxidations occurring in the sea are confined.

The cause of the very low pH (7·56) observed at the shallow depth of 20 m. at Station 12 is, however, not clear. Judging by the order of magnitude of low pH values found in other regions of the Arabian Sea, where more intense oxidation is known to be taking place, the occurrence of this low pH value cannot be entirely explained on oxidation grounds. When we examine the temperature observations we find that the surface temperature (23·46° C.) at this station is the lowest surface temperature observed at any of our stations in the Gulf of Aden. Moreover, we find that whereas the magnitude of the maximum pH vertical gradient at Stations 13 and 14 corresponds well with the magnitude and trend of the maximum vertical temperature gradient, it is much higher at Station 12 than one would expect from the temperature gradient. Although these facts do not throw much light on the cause of the abnormally low value of pH, they suggest that conditions at Station 12 were disturbed somehow by an unknown agency, such as an influx of fresh water from the Arabian coast.

The minimum pH layer is sharply separated from the surface layer, which is very thin at this time of the year, by a well-developed vertical pH gradient. The steepest gradient occurs between the depths of 10 and 20 m., where it amounts to 3·7 pH units and is by far the largest gradient found in our area of investigation. At Station 13 it is 1·7 units and at Station 14 it is 2·9 units and it occurs at a lower level, namely, between 30 and 40 m. It is interesting to note that the greatest vertical temperature gradients occur at the same levels as the greatest pH gradients. This simultaneous development of very pronounced vertical gradients of pH and temperature at the same levels suggests that in the Gulf of Aden the depth of the surface layer as a seat of phytoplanktonic activity is restricted in September by the sharp thermocline. Further, the presence of a well-developed density gradient near the surface cuts off the rich supply of nutrient salts stored in the deep water from the surface waters and consequently the phytoplanktonic activity becomes confined to a very thin layer.

In the deeper water below the minimum pH layer the values of pH are relatively high ; the origin of this water has already been shown to be the Red Sea bottom current. The course taken by the isolines within this deep water indicates that the Red Sea bottom current flows out along the African coast in large volumes.

Section B : Conditions in May (Text-fig. 6).—On the homeward journey observations were repeated along Section B at the same three stations of the previous season ; the stations are now known as 202, 201 and 200.

The surface pH varies from 8·05 on the Arabian side of the Gulf to 8·14 on its African side. The maximum pH throughout this section occurs invariably at a depth of 10–20 m. ; the occurrence of the zone of maximum phytoplanktonic activity below the surface and not at the surface has already been explained as being possibly due to the strong light at the surface. Below this peak the pH value decreases with depth until it reaches a minimum at a depth of 200 m., below which it increases again to a secondary maximum near the bottom at Stations 201 and 202. However, at Station 200, which lies over the deep gully, the pH decreases again to a secondary minimum in the vicinity of the bottom of the gully. Unfortunately, no observations were secured during the previous season from depths below 1000 m. in the gully, but it is not improbable that the pH-depth curve would exhibit a similar secondary minimum at depths greater than 1000 m.

In May, at the beginning of the summer, the heating-up of the surface has begun and the vertical pH gradients are distinct, although not steep, as they were in September at the end of the summer season.

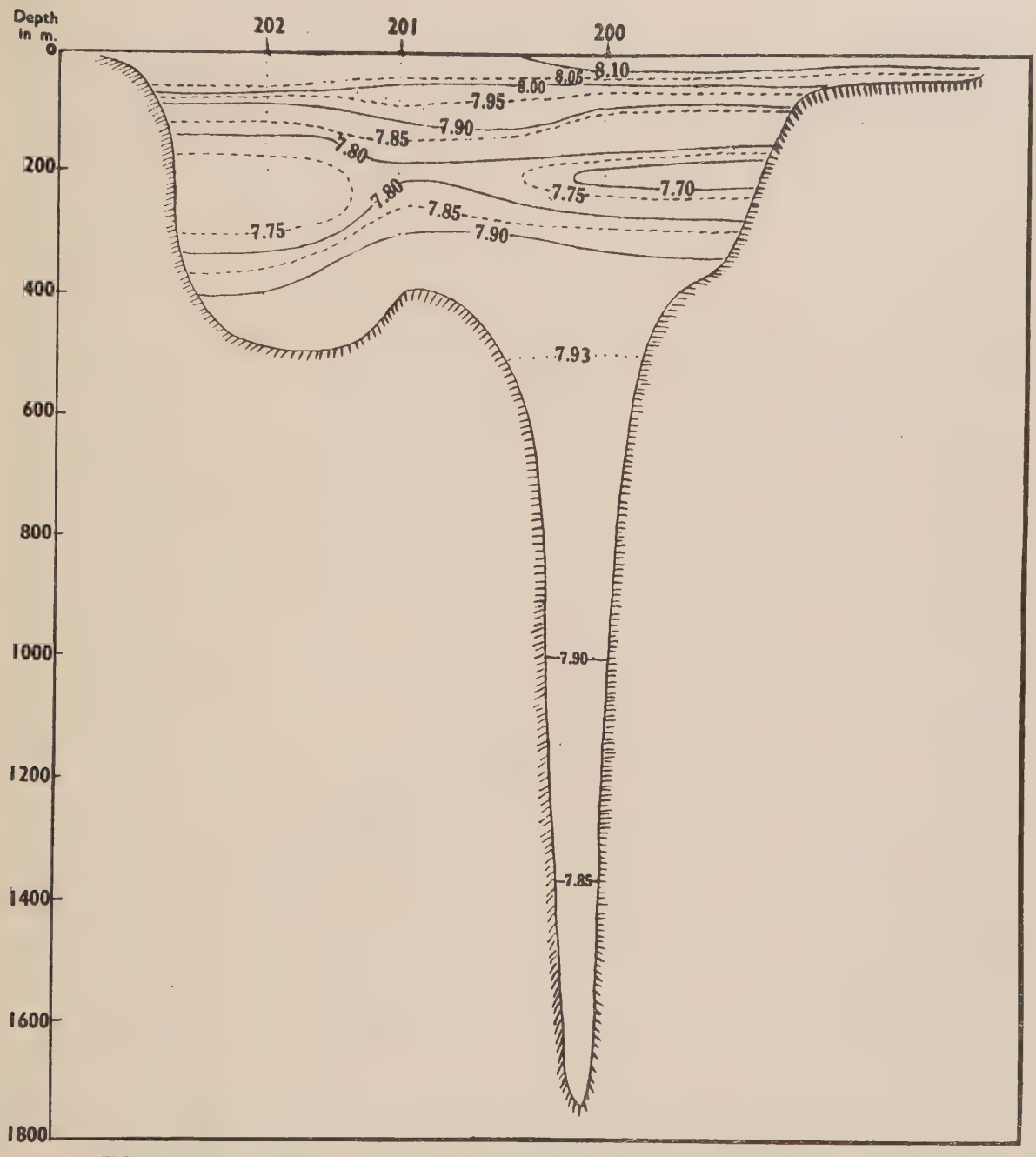

FIG. 6.—THE DISTRIBUTION OF pH ALONG SECTION B ACROSS THE WESTERN END OF THE GULF OF ADEN (MAY).

The average pH of the surface waters is, on the whole, higher than it was in September and the thickness of the surface layer is greater (50–90 m.). These facts indicate a higher phytoplanktonic activity, which can be explained as due to the deeper position of the thermocline at this season, the lower limit of the phytoplanktonic layer being consequently

pushed deeper. Moreover, since the density gradient is not yet steep enough to shut off the supply of nutrient salts from the surface waters, the activity of phytoplankton causes the pH to be higher. It is obvious that in May the zenith of this activity has already been passed.

Below the surface layer the minimum pH layer is seen to be much reduced in thickness. We have already seen, when describing Section A, that this mass of water failed to pass through the Straits of Bab-el-Mandeb into the Red Sea on account of the volume and flow of the Red Sea deep current. The pH distribution in this profile throws further light on the movement of this water mass. Opposed by the Red Sea deep current it is turned back and is seen in the profile as if moving in on one side of the Gulf and out on the other side. The volume of this mass is greater on the Arabian side (*ca.* 180 m.) than on the African side (*ca.* 100 m.) and has a nucleus at a higher level (at 200 m.) on the latter side than on the Arabian side (at 240 m.). Its small thickness on the African side, which is possibly due to mixing with Red Sea water possessing a relatively higher pH, and the higher level of its nucleus, which is apparently due to the upward thrust given to it by the projecting ridge lying in the position of Station 201, suggest that this was the outflowing or eastward-moving portion of the mass, while its in-flowing or westward-moving portion lay on the Arabian side.

In the deep water below the minimum pH layer the pH is relatively high, and we have already traced the origin of this water to the outflowing Red Sea deep current. As seen from the profile, the volume of this water is, on the whole, much larger than in the corresponding profile for September. It now covers the great depths on the Arabian side, whereas in September there was hardly any Red Sea water there.

In the depths of the gully (below 1000 m.) the pH diminishes to a value of 7·82. We have already suggested (p. 140) that this decrease in pH is due to the westward drift of a low pH current on the bottom of the Gulf.

Section C : Conditions in September (Text-fig. 7).—Observations of pH at four stations (19, 20, 21 and 17) were taken along Section C in September.

The surface pH varies from 8·02 to 8·05; the maximum pH value of the suface water was frequently found more often at a depth of 10–20 m. than at the surface. Below this peak the pH decreases, at first suddenly and then gradually, until it reaches a primary minimum value of 7·68-7·72 at a depth varying from 40 to 200 m., but with further increase of depth the pH increases again until it attains a secondary maximum value of 7·84 on the Arabian side of the Gulf and of 7·94 on the African side at a depth of 600–800 m. Below the depth of secondary maximum the pH decreases again with depth until it reaches a secondary minimal value of 7·68–7·80 at great depths at all stations on this section except Station 17.

The levels at which the greatest vertical pH gradients occur lie between 10 and 40 m., and the values of the gradient vary between 2·2–2·9 pH units. The simultaneous development of steep pH and temperature gradients at the same levels strengthens the suggestion already made that the depth of the phytoplanktonic activity layer in September is restricted by the thermocline.

The vertical distribution of pH along this section is essentially the same as along Section B in September (*cf.* Text-figs. 5 and 7), but the profile of this section exhibits in a clearer manner four different water layers.

The surface layer, which varies in thickness from 10 to 40 m., is distinctly separated

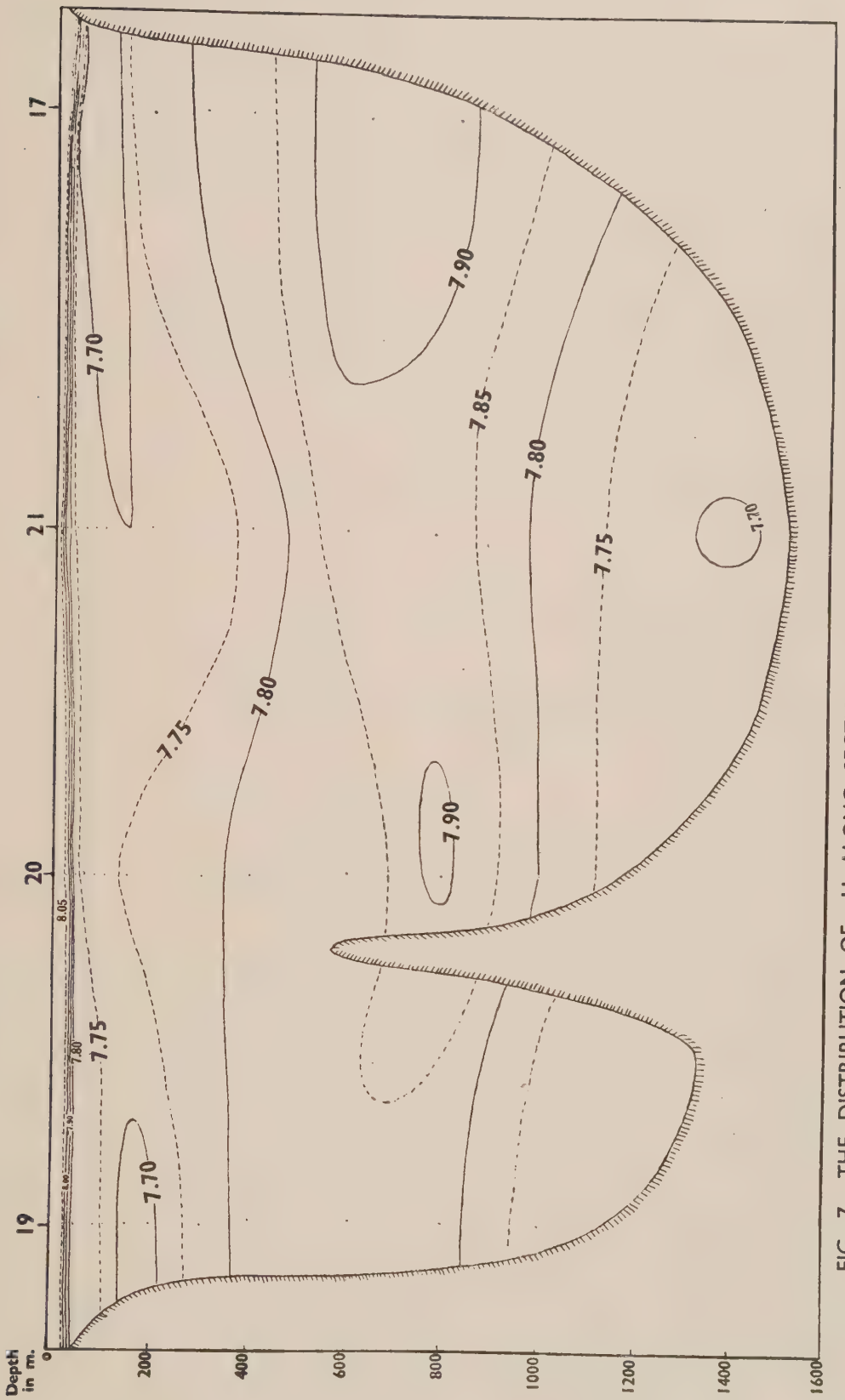

FIG. 7.—THE DISTRIBUTION OF pH ALONG SECTION C BETWEEN ADEN AND BERBERA (SEPTEMBER).

from the primary minimum pH layer by a well-developed vertical gradient. The latter layer represents the sub-surface current which flows through the Straits of Bab-el-Mandeb. The thickness of this layer is greatest at Station 21, and is greater on the Arabian side than on the African side. Its small thickness on the African side is probably due to mixing with the Red Sea bottom current, which flows out in large volumes along the African coast and possesses relatively higher pH values. We have already attributed the low values of pH within this layer to processes of organic oxidation due to relative stagnation.

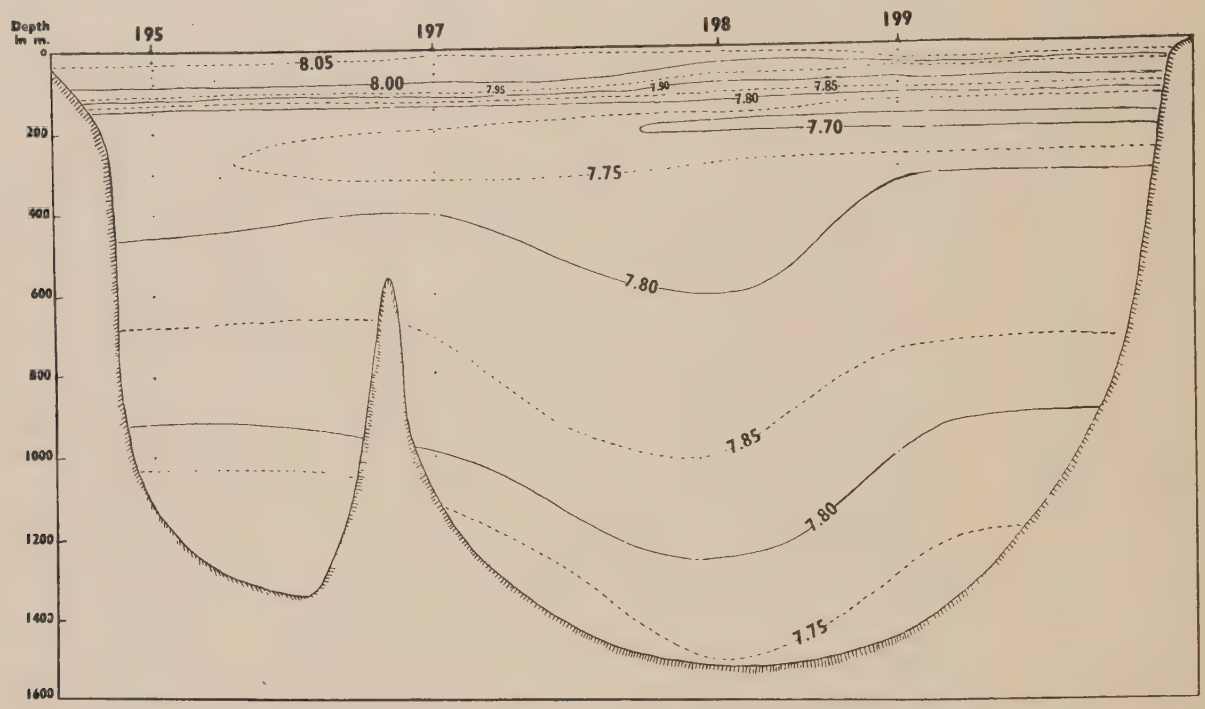

FIG. 8.—THE DISTRIBUTION OF pH ALONG SECTION C BETWEEN ADEN AND BERBERA (MAY).

Below the primary minimum pH layer is a tongue-shaped mass of water with an axis at about 700 m. and with a comparatively high pH. This mass represents the out-flowing bottom current from the Red Sea.

In the great depths of the Gulf we find a fourth mass of water with low pH values. From its temperature and salinity this water seems to have originated outside the Gulf and to represent a deep current from the Arabian Sea which finds its way into the Gulf of Aden and creeps westwards along its bottom. The low values of pH within this water are probably due to organic oxidations on account of its age and slow movement.

Section C: Conditions in May (Text-fig. 8).—Observations were repeated along Section C in May ; the stations are now numbered 195, 197, 198 and 199. Station 199, however, does not coincide in position with Station 17.

The surface pH varies from 8·03 to 8·08 ; at some stations the maximum pH occurs again below the surface. The pH remains constant or changes slightly and gradually with increase of depth in the surface water. At a depth of 100–150 m. the pH falls, at first suddenly and then gradually, until it reaches a minimum value of 7·72–7·76 at a depth of 300 m. in the northern half of the Gulf and of 7·68–7·69 at a depth of 200 m. in

the southern half. Below the depth of this minimum value the pH increases with further increase of depth until it reaches a secondary maximum value of 7·84–7·68 at a depth of 800–1000 m. Below this the pH drops to a secondary minimum value of 7·73–7·76 near the bottom. At Station 197, however, observations were not taken near enough to the bottom to demonstrate this secondary minimum.

The profile of this section shows that in this season also there are four water layers with a similar arrangement to that found in September. The surface layer is, on the whole, much thicker here, as it extends down to 100 m. at some stations, and the average values of pH within this layer are higher. The lower limit of the phytoplanktonic layer has been pushed deeper by the thermocline and the density gradient is not yet steep enough to shut off the supply of nutrient salts.

Below the surface layer is the primary minimum pH layer which represents that water mass, which fails to pass through the Straits of Bab-el-Mandeb on account of the great volume of the Red Sea deep current and is turned back into the Gulf. It was also suggested (*vide supra*, p. 144) that the eastward-moving portion of this mass lay on the African side. In this profile the lowest pH values within this layer are found on the African side, which shows that oxidation on that side is in a more advanced stage on account of the age of that portion of the water layer.

The Red Sea deep current is represented by the secondary maximum pH layer, which is seen in the profile to have a greater thickness than it had in September. Finally, we have the secondary minimum pH layer, which we have assumed to represent a current from the open Arabian Sea creeping westwards along the bottom of the Gulf. This layer is now much thinner than it was in September and it seems, therefore, that its volume is subject to seasonal changes.

Section D : Conditions in October (Text-fig. 9).—Observations along Section D were made in October at three stations (32, 38 and 25).

The surface pH varies from 8·05 on the northern side of the Gulf to 8·09 on the southern side. Below the shallow depth of 10 m. the pH falls rapidly with increase of depth and then gradually until it reaches a primary minimum value of 7·76–7·71 at a depth of 50–100 m. Still deeper the pH rises again until it reaches a secondary maximum value of 7·86–7·92 near the bottom at Stations 25 and 32 and at a depth of 200 m. at Station 38. At the latter station the pH decreases again to a secondary minimum value of 7·75 at a depth of 400 m. and then increases to a tertiary maximum of 7·88 at a depth of 800 m., below which it diminishes to a tertiary minimum near the bottom (*vide* Text-fig. 2, Station 38).

The greatest vertical pH gradient along this section is well pronounced, amounting to 1·00–1·50 pH units, and occurs between the depths of 10–20 m. The simultaneous development of well-pronounced pH and temperature gradients at the same levels along this section is in common with all our observations in the Gulf in September.

The lapse of time between the observations at the different stations along this section, the position of the section itself at the mouth of the Gulf, where several water masses are bound to meet and mix, and the complicated topography of this eastern region combine to make it difficult to form a clear picture of the water layers in this profile. Moreover, the lack of observations in the long stretch between Stations 38 and 25 makes our presentation of the conditions across the central part of the Gulf only approximate.

Nevertheless, some of the general features common to other sections in the Gulf can be pointed out without difficulty. Below the surface layer, which is only about 10 m.

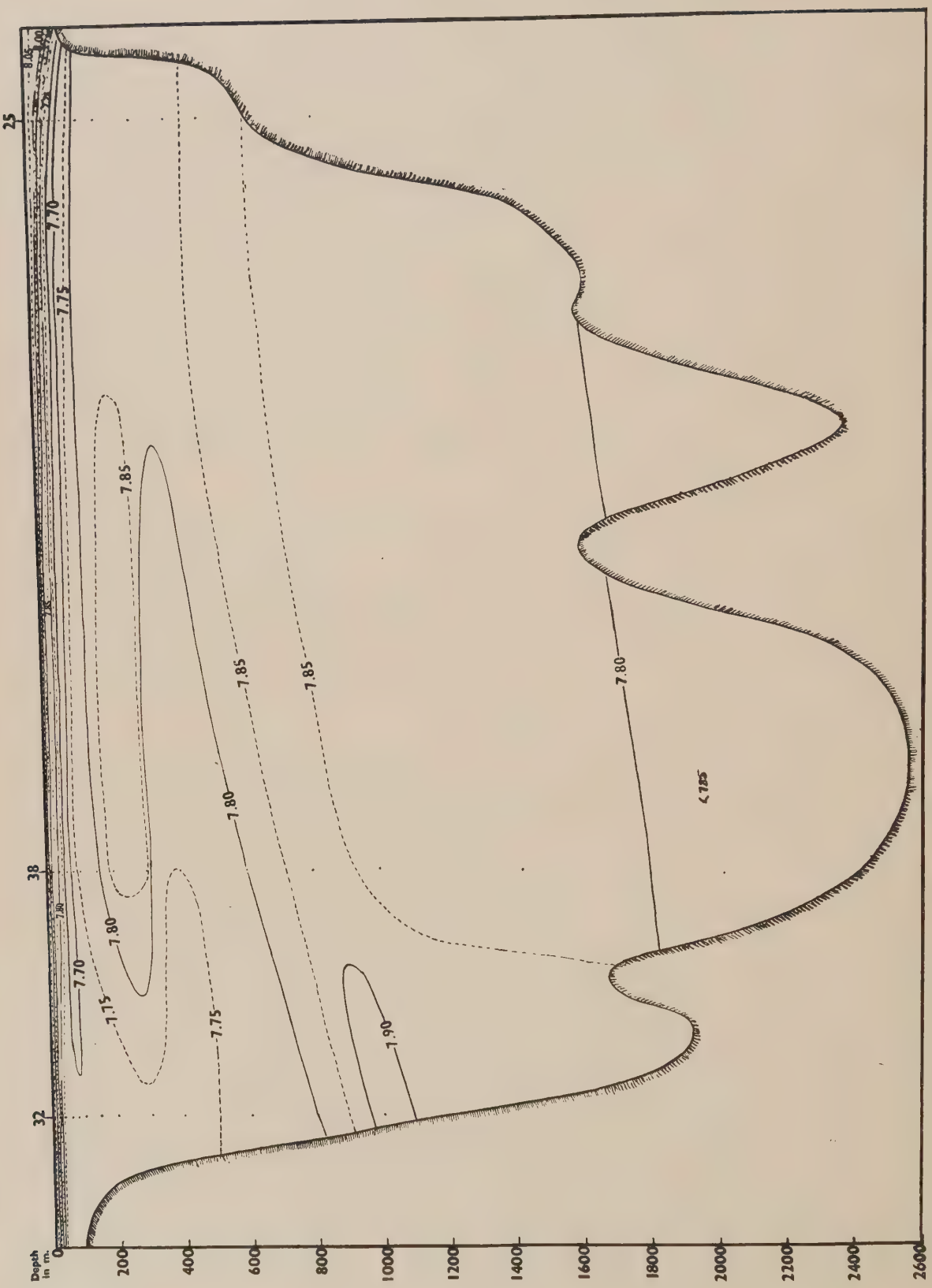

FIG. 9.—THE DISTRIBUTION OF pH ALONG SECTION D ACROSS THE EASTERN END OF THE GULF OF ADEN (OCTOBER).

thick, is the minimum pH layer which attains a considerable thickness on the northern side of the Gulf. Along the remainder of the section its thickness is, however, reduced owing to mixing with other water masses. As the outflowing Red Sea water reaches this part of the Gulf it becomes difficult to trace it clearly. We find, however, at a depth of 1000 m. at Station 32 a water mass, with a pH value of 7·91, which represents the Red Sea bottom current. At a depth of 200–300 m. in the position of Station 38 we find another mass with relatively high values of pH (7·85). The origin of this mass is not clear, but it probably represents an offshoot of the main Red Sea water mass. The deep parts of the Gulf are seen to be filled with water having pH values between 7·80–7·85.

Section D : Conditions in May (Text-fig. 10).—Observations of pH along Section D were repeated in May at two stations only (181 and 183).

The surface pH varies from 8·06 to 8·08 ; descending below the surface the pH changes slightly with depth until it reaches a minimum value of 7·69–7·70 at a depth of 200 m. With increasing depth the pH rises until it reaches a secondary maximum of 7·82–7·85 at a depth of 800–1000 m., below which it falls to a secondary minimum value of 7·70–7·75 in the vicinity of the bottom.

The arrangement of the water strata in the profile of this section is very similar to that of Section C (May) and calls for but little comment. It is seen that the surface layer is now much thicker than it was in October and possesses higher pH values. Below the surface layer is the primary minimum pH layer. The Red Sea deep current is represented by a water mass with pH values varying from 7·80–7·85. Finally we find the secondary minimum pH layer, which fills the deeper parts of the Gulf and represents what we assumed to be a current from the open Arabian Sea, creeping westwards along the bottom of the Gulf. The pH values within this deep water are now lower than they were in October and it seems, therefore, that the character of this water, as well as its volume, is subject to seasonal changes.

Section E : Conditions in October (Text-fig. 11).—Observations of pH in the Socotra Channel were made along Section E at two stations (23 and 30) in October. The pH of the surface waters is comparatively high and uniform in the upper 20–40 m. With increasing depth the pH decreases until it reaches a primary minimum value of 7·79–7·83 at a depth of 150 m., below which it increases again to a secondary maximum at a depth of 300 m. Below this the conditions are different north and south of the Socotra-Guardafui ridge. At Station 30 the pH-depth curve exhibits two weak minima, while at Station 23 it shows only one minimum.

Below the surface layer there is a large water mass with intermediate pH values varying from 7·85–7·95. This mass is split up into two parts by a weak minimum represented by an intrusive tongue of water at a depth of 150 m. in the position of Station 23, but the presence of a minimum pH layer in the usual sense, *i. e.* as defined by values less than 7·80 is practically non-existent. It is improbable that this weak minimum is due to an error of observation, but is rather a result of the unusual conditions in this region, where, owing to the peculiar position of the section, several water masses come presumably from various directions. At a depth of 600–800 m. on the northern side of the ridge there is another body of water with similar intermediate values of pH, and it is possible that this body of water is the continuation of the water above it, and that it has been split off by the secondary weak minimum found at a depth of 400 m. This body of water can hardly be described as representing the Red Sea bottom current, since the outflow of

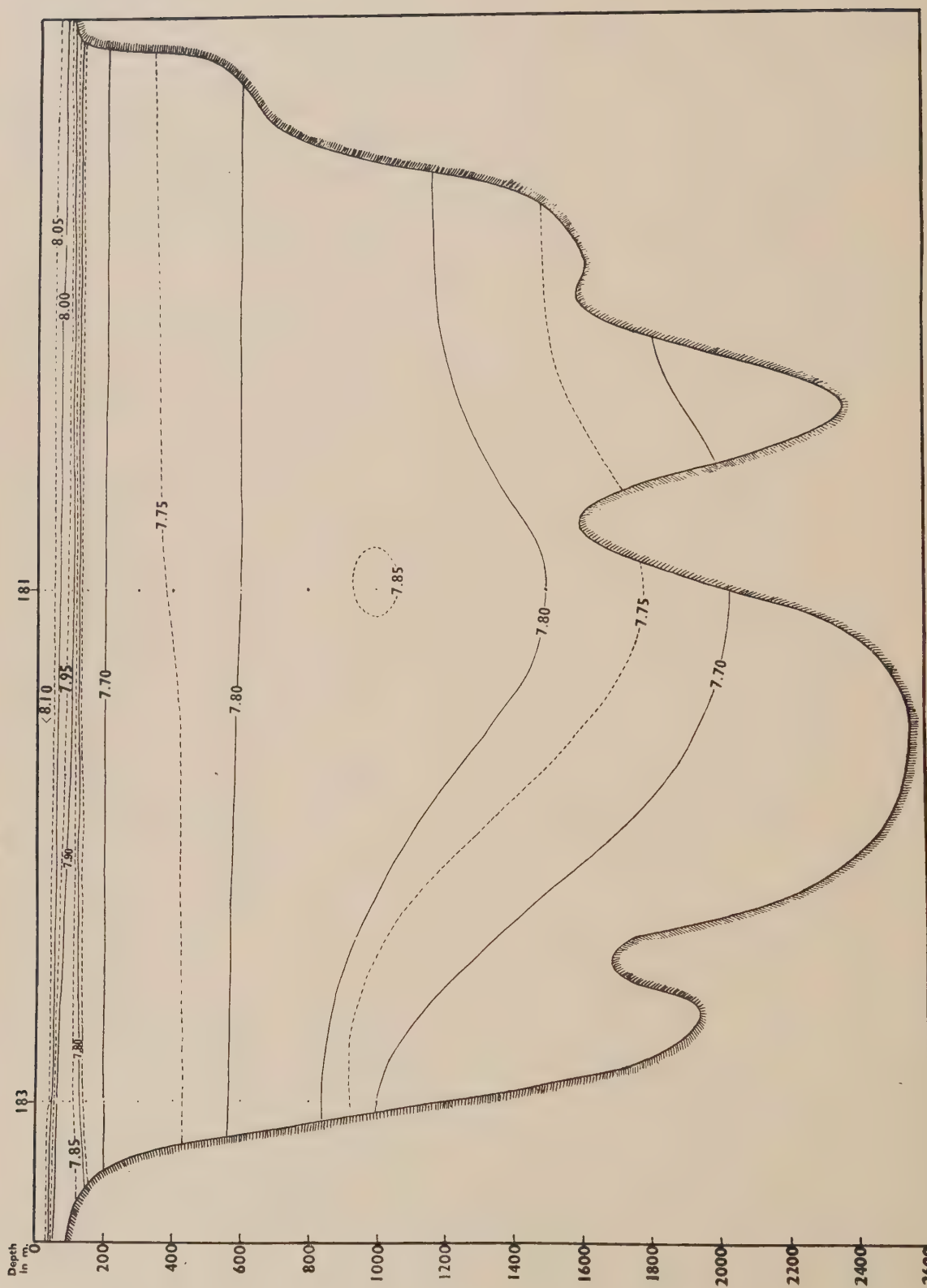

FIG. 10.—THE DISTRIBUTION OF pH ALONG SECTION D ACROSS THE EASTERN END OF THE GULF OF ADEN (MAY).

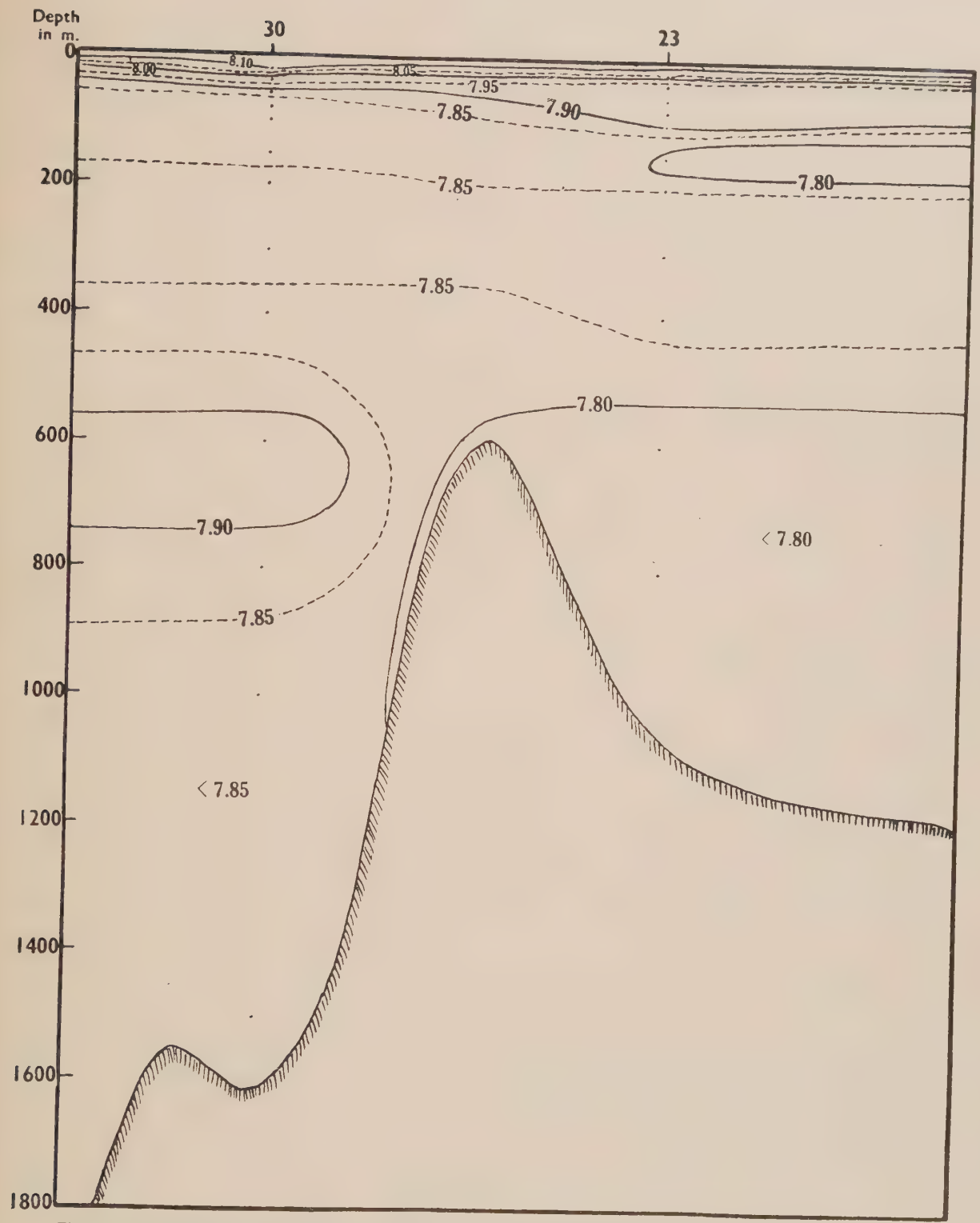

FIG. 11.—THE DISTRIBUTION OF pH ALONG SECTION E THROUGH SOCOTRA CHANNEL (OCTOBER).

this current is small in this season and has already been seen to be vanishing in the profile of Section D (October).

The deep water lying north of the ridge has pH values less than 7·85, and is seen to have originated south of the ridge. This water passes over the ridge into the Gulf of Aden and it is probable that the current which creeps westwards along the bottom in the Gulf of Aden is its continuation.

Section E : Conditions in May (Text-fig. 12).—On the return journey observations were repeated along Section E in May at the same two positions (Stations 174 and 175). We find again that conditions are different north and south of the Socotra–Guardafui ridge. South of the ridge (Station 174) we find that below the thick surface layer the pH falls somewhat abruptly until it reaches a minimum value (7·73–7·74) at a depth of 200–400 m., and then increases slightly near the bottom.

North of the ridge we find below the thinner surface layer a body of water having intermediate values of pH (7·88–7·99) with a nucleus about a depth of 200 m. As this body of water cannot be said to have originated in the Gulf of Aden, with the water strata of which we are now familiar, it is reasonable to assume that it has its origin in the open ocean. It is also clear that this water does not approach the position of Station 30 in the main over the ridge, but rather from a diagonal direction, which is possibly easterly to south-easterly. This water will be traced later to an important layer with similar character found in the open ocean and known as the Antarctic intermediate current.

Below this body of water the pH of the deeper water is low and uniform throughout the entire water column north of the ridge. This deeper water is also seen in this profile to have originated south of the ridge, and since it is similar in character to the current creeping along the bottom in the Gulf of Aden, the latter can be considered as its continuation. A similar conclusion regarding the origin of this bottom current in the Gulf during the last season has already been reached. It is not possible at this stage to trace the source of this water in the open ocean any further, especially since the number of observational stations on this section is very limited.

The deep Red Sea current cannot be detected in this profile, and it is possible that the position of this section does not coincide with the main direction of its flow. It is equally possible that by the time it leaves the Gulf of Aden its pH has fallen so low that it becomes difficult to trace.

The Gulf of Oman, the Arabian Sea, and the North-Western Indian Ocean.

In the Gulf of Oman, the Arabian Sea and the north-western Indian Ocean area pH observations were made along eight sections (F–M), two of which run off the South Arabian coast, one parallel to it, one in the Gulf of Oman, one off the African coast and three across the ocean between the Asiatic and African coasts.

The Arabian Coast.

Observations along sections F and G off the South Arabian coast and along Section H, which runs parallel to the coast, were made in October–November.

Section F (Text-fig. 13).—This section runs off the South Arabian coast in the vicinity of Kuria Muria Islands, and observations along it were taken at two stations, 41 and 43,

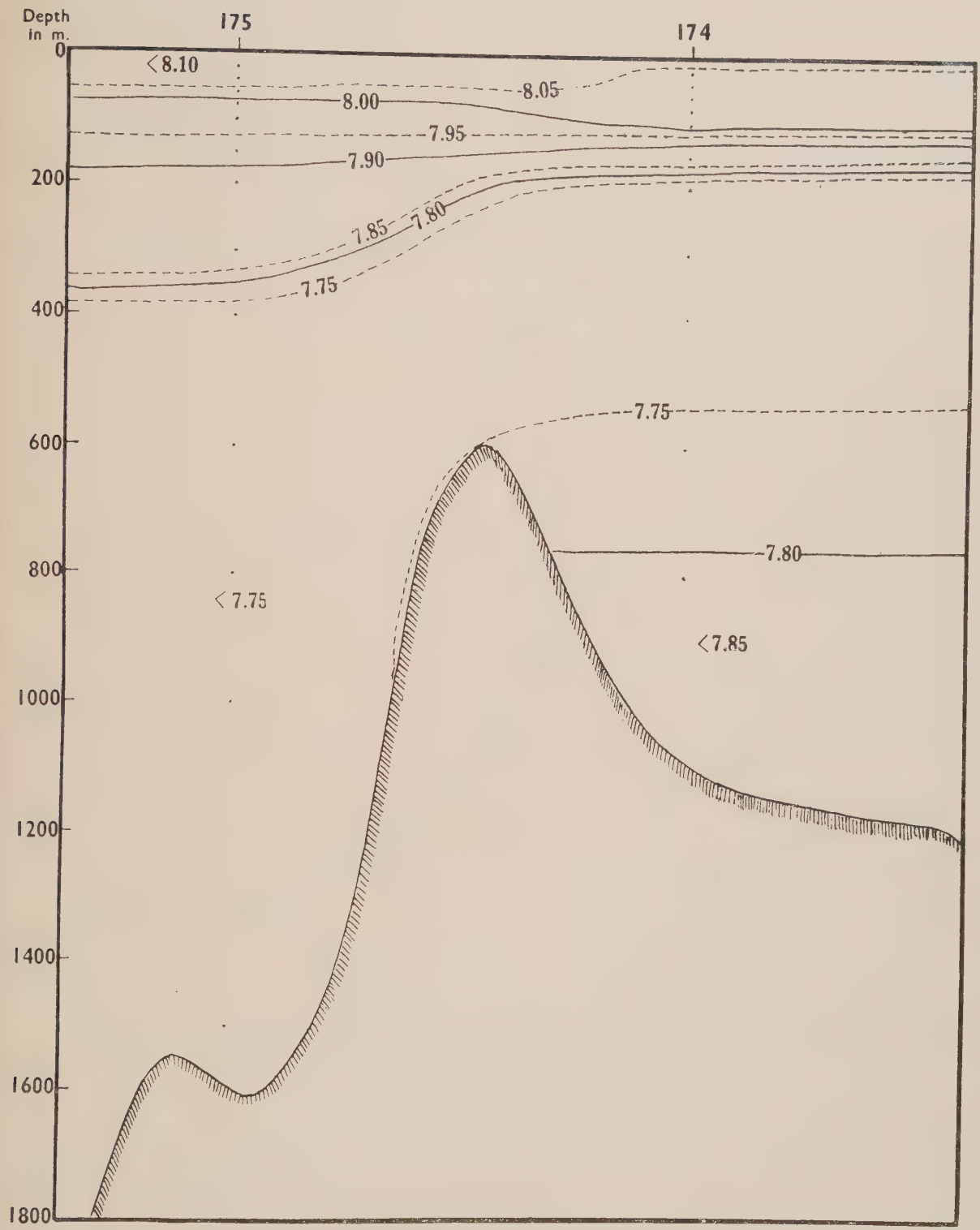

FIG. 12.—THE DISTRIBUTION OF pH ALONG SECTION E THROUGH SOCOTRA CHANNEL (MAY).

in October. The two main features in this profile are the concentration of pH isolines in the immediate neighbourhood of the surface and the massive thickness of the minimum pH layer as defined by pH values less than 7·80.

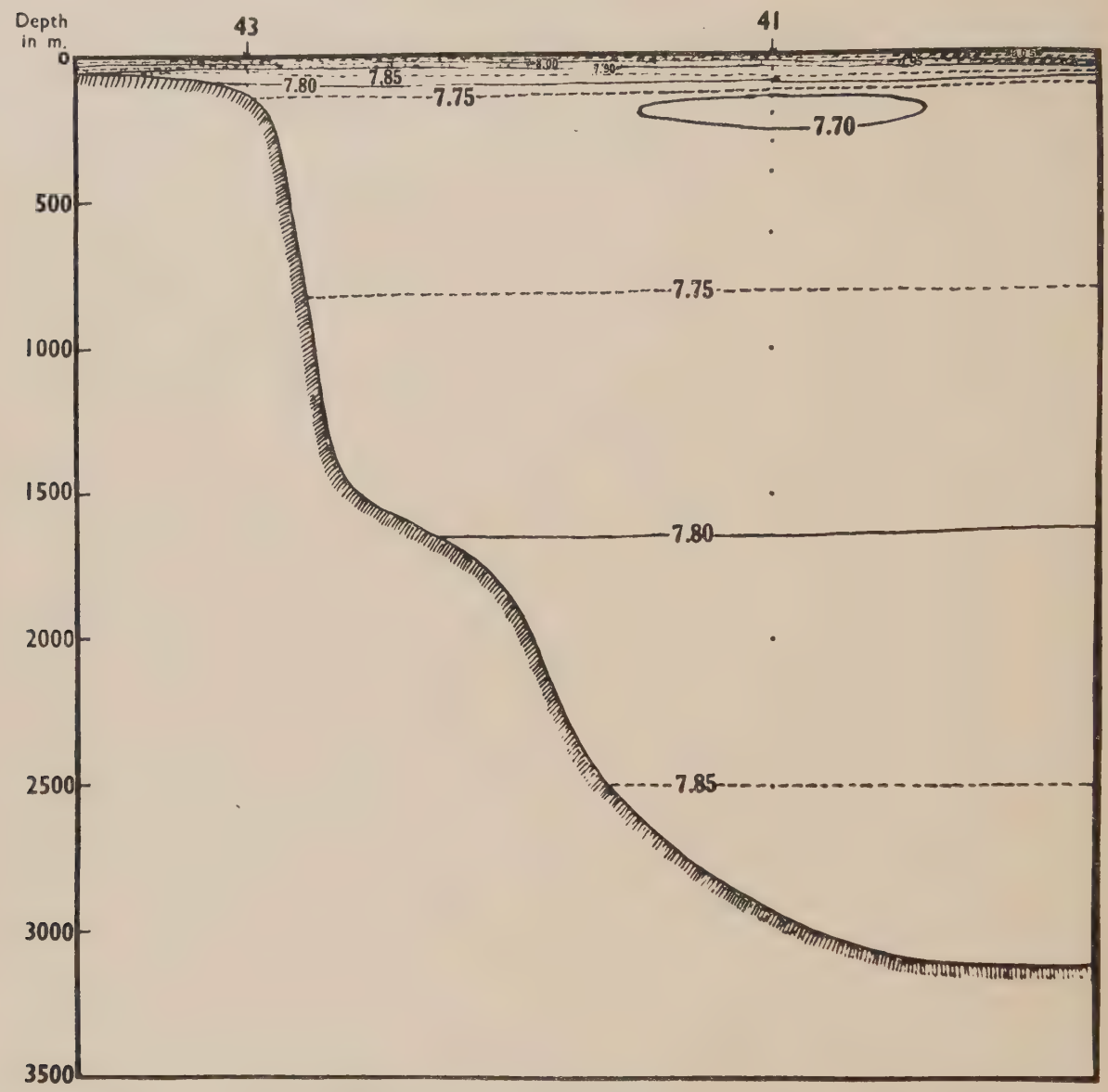

FIG. 13.—THE DISTRIBUTION OF pH ALONG SECTION F OFF THE ARABIAN COAST IN THE VICINITY OF KURIA MURIA ISLANDS.

The surface pH varies from 8·07 at the seaward station to 8·11 at the inshore station, indicating a higher phytoplanktonic activity in the inshore waters. The surface layer, which amounts in thickness only to 30–40 m., is separated from the layer below it by pronounced vertical gradients. It is noteworthy that along this section also these gradients occur at about the same depth as the principal thermocline.

Below the surface layer the pH falls abruptly and continues to fall with increasing depth until it reaches a minimum value of 7·68 at a depth of 150 m. The thickness of the minimum pH layer amounts to about 1000 m., thus revealing the presence of oxidation

processes on a vast scale. As we have already seen in the profiles of the Gulf of Aden sections, great thickness of the minimum pH layer and a position immediately below the surface layer seem always to be associated with the presence of a sharp thermal boundary below the surface layer. The minimum pH layer is therefore in the first place a result of the hydrographical and meteorological conditions in these coastal regions. As we shall see later, this low pH water formed in these coastal regions is the source of the so-called North Indian deep current, which moves southwards.

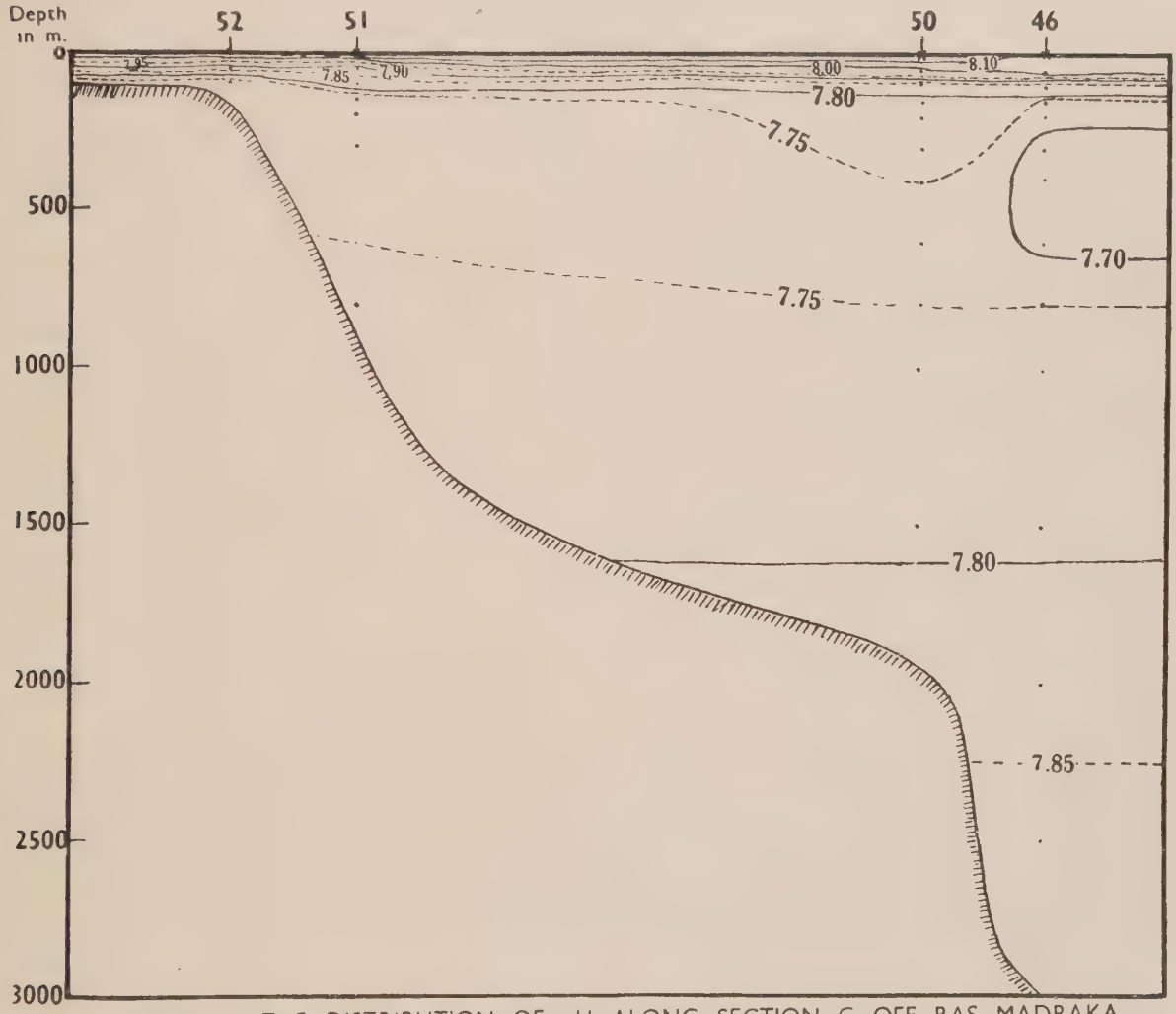

FIG. 14.—THE DISTRIBUTION OF pH ALONG SECTION G OFF RAS MADRAKA ON THE ARABIAN COAST.

At the deep seaward station the pH reverses its vertical gradient below the depth of minimum pH and continues to increase until it reaches values higher than 7·80 in the deep water. This deep water will be shown later to have its origin in the northward movement of the Antarctic intermediate current.

Section G (Text-fig. 14).—This section runs off the South Arabian coast in the vicinity of Ras Madraka and observations along it were made at four stations (46, 50, 51 and 52) in October–November.

The vertical distribution of pH along Section G is essentially the same as in the last section (*cf.* Text-figs. 13 and 14). The surface pH is again higher (8·13–8·14) at the

inshore stations than it is further to seaward, and is, on the whole, relatively high compared with the surface pH in other regions, reflecting a more intense phytoplanktonic activity.

The surface layer is separated from the layer below by distinct gradients, which occur at about the same depths as the principal thermocline.

The thickness of the minimum pH layer, which amounts to about 1470 m., is the most marked feature of pH distribution along this section. In the deep water underlying this minimum pH layer the pH is comparatively high. This deep water does not cover the continental slope to any great extent, and has obviously come from the south.

It is thus seen that we can distinguish at least three water strata off the South Arabian coast: a surface layer, the minimum pH layer which corresponds to the North Indian deep current, and the deep water, which comes from the south.

Section H (Text-fig. 15).—Observations of pH along Section H, which runs parallel to the South Arabian coast, were made at three stations (39, 40 and 82) in October–November.

The distribution at Station 82 is essentially similar to that along Sections F and G. Here we find a massive minimum pH layer below the surface layer and finally the deep water. At Station 39 we find, however, a less massive minimum pH layer separated from the surface layer by a large body of water with intermediate values of pH. At Station 40 this latter water constitutes the bulk of the water column. Large volumes of this water, characterized by intermediate pH values, are thus met with for the first time in our area. The minimum pH layer is practically non-existent here and its usual position in the water column has been occupied by this water with intermediate pH values. From our description of the horizontal distribution of pH it will be seen that this water owes its presence to the northward movement of the Antarctic intermediate current. It is further noticeable that the water between the surface layer and the minimum pH layer in the position of Station 39 is in continuation with the main column of this water, which is split up there into an upper and a lower part by the intrusion of the minimum pH layer. We may, therefore, speak of the upper Antarctic intermediate current and the lower Antarctic intermediate current.

Whereas the lower Antarctic intermediate current fills the great depths in this profile, the upper current sends a branch to the westward, here found below the surface layer at Station 39. This is probably the source of the water with intermediate pH values found in similar position north of Socotra–Guardafui ridge at Station 30. A less marked easterly branch of the upper Antarctic intermediate current is also noticeable.

Gulf of Oman.

Section I (Text-fig. 16).—Observations of pH were made in November along Section I at four stations (76, 81, 61 and 83).

The main features of the profile of this section are essentially similar to those of the sections off the South Arabian coast, namely, the concentration of isolines near the surface and the great thickness of the minimum pH layer. The surface layer varies in thickness from 20 to 60 m. The greatest vertical pH gradients along this section occur strictly at the same depths as the principal thermocline. Below the surface layer the pH falls abruptly and then gradually with increasing depth until it reaches a minimum value of 7·62–7·72 at mid depths (600–1000 m.). At Station 76, the most northerly one, there is, however, an intrusive tongue of water with comparatively high values of pH, which gives

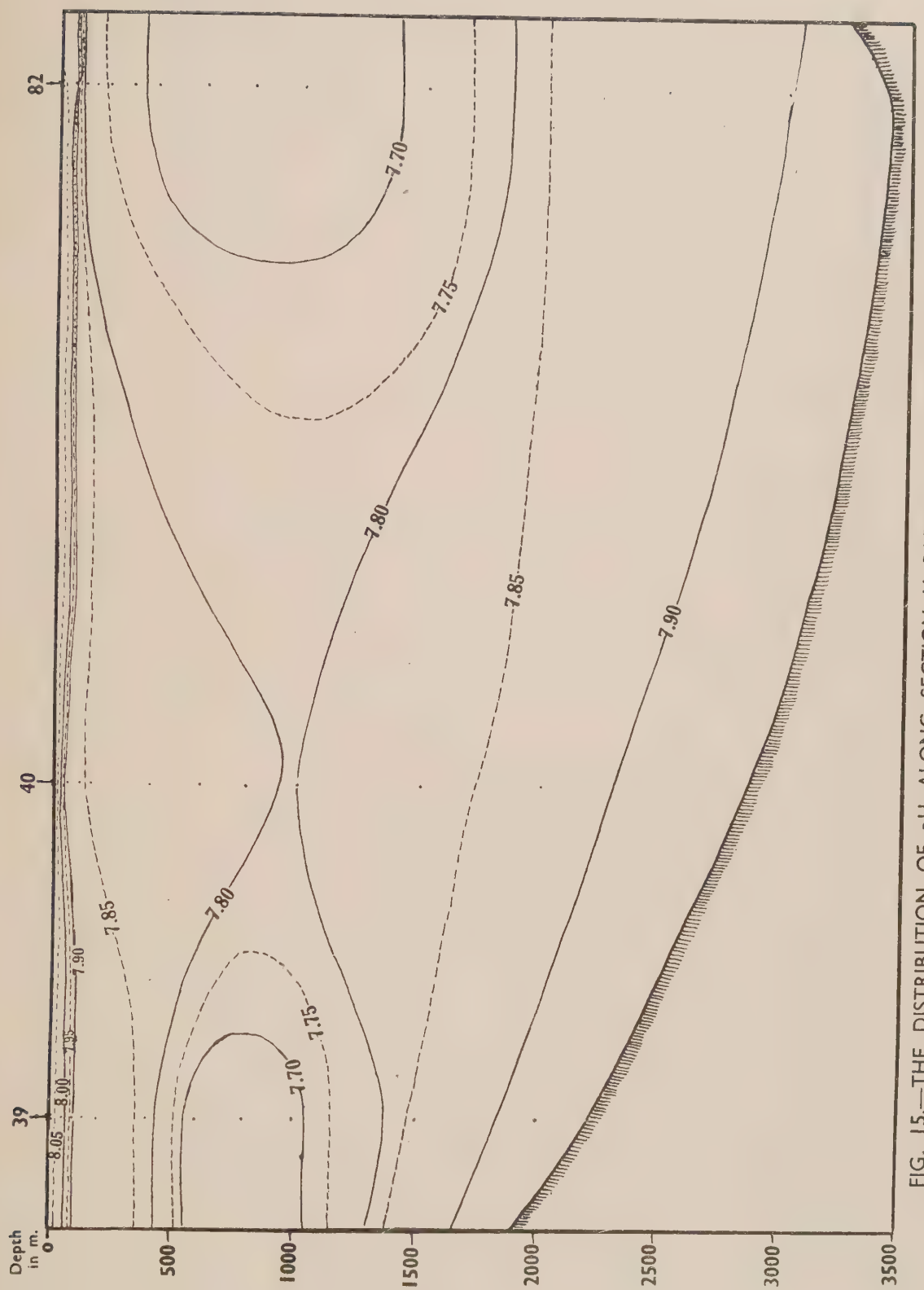

FIG. 15.—THE DISTRIBUTION OF pH ALONG SECTION H PARALLEL TO THE SOUTH ARABIAN COAST.

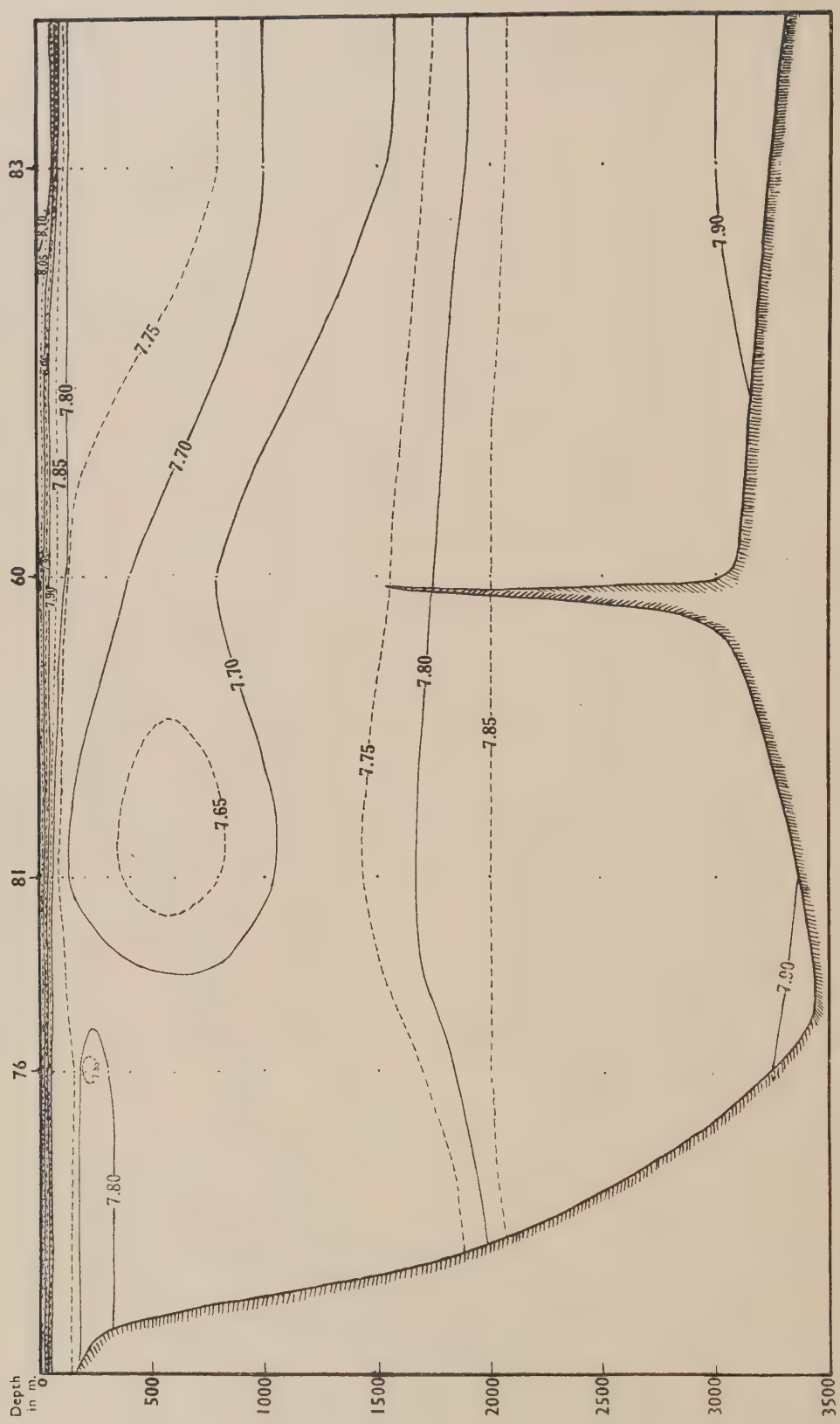

FIG. 16.—THE DISTRIBUTION OF pH ALONG SECTION I IN THE GULF OF OMAN.

rise to a secondary maximum at a depth of 200 m. Although we have not secured any observations from the Persian Gulf, it seems very probable that this intrusive tongue flows out from the Persian Gulf as this is the only obvious source.

The volume of the minimum pH layer is well marked in this profile and it is here that it attains a very great thickness (1670–1750 m.). It is also in this profile that the upper boundary of the minimum pH layer (upper 7·80 isoline) shows a closer approach to the surface than in any other section in the Arabian Sea or the north-western Indian Ocean. Its lower boundary (lower 7·80 isoline) lies deeper here than it is in any other section. If the assumption put forward above, that the boundaries of the minimum pH layer represent the limits to which organic oxidations in the sea are confined, is correct, the minimum pH layer in this profile must be the seat of far-reaching oxidation processes. The order of magnitude of the lowest pH values within this layer suggests that a relatively more intense oxidation is taking place here than anywhere else in the Arabian Sea or the north-western Indian Ocean. It is interesting to note in this connection that the lowest pH values within this layer are found at Station 81, which lies off Ras el Hadd, a locality remarkable for the presence of hydrogen sulphide in the bottom deposits obtained from its vicinity.

When we examine the temperature observations along this secton we find that there is a well-pronounced temperature gradient (and consequently a density gradient) near the surface. We have already assumed that the presence of such a sharp boundary between the surface and the minimum pH layer makes the latter dependant for its oxygen supply on lateral exchanges which leave it in a state of relative stagnation. This low pH water formed here and off the South Arabian coast moves, as we shall prove later from our description of horizontal distribution, southwards as the North Indian deep current. The way in which the pH isolines within this layer slope down as they run to the south suggests that this water sinks on its way southwards.

Below the surface layer and above the upper boundary of the minimum pH layer there is, at the most southern station on the section, a band of water with pH values of *ca.* 7·85. The origin of this water is the easterly component of the upper Antarctic intermediate current described under Section H.

In the deeper water below the lower boundary of the minimum pH layer the pH becomes higher again (7·85–7·90). This water, as well as the deep water found in sections off the South Arabian coast, will be proved, when describing the horizontal distribution of pH, to have its origin in the northward movement of the Antarctic intermediate water.

To sum up, the chief features of the vertical distribution of pH along Section I are : (1) The concentration of the isolines near the surface ; (2) the massive thickness of the minimum pH layer ; (3) the low magnitude of the minimum pH values ; (4) the existence of the Persian Gulf water at the northern station as an intrusive tongue within the minimum pH layer (5) the existence at the southern station of a band of water with intermediate pH values between the surface layer and the minimum pH layer; and (6) the relatively high pH values of the deep waters.

Sections between India and Africa.

Section J (Text-fig. 17).—During December pH observations were made between Bombay and Mombasa at seven stations (91, 92, 93, 95, 97, 101 and 102) along Section J, which runs in a north-east to south-west direction.

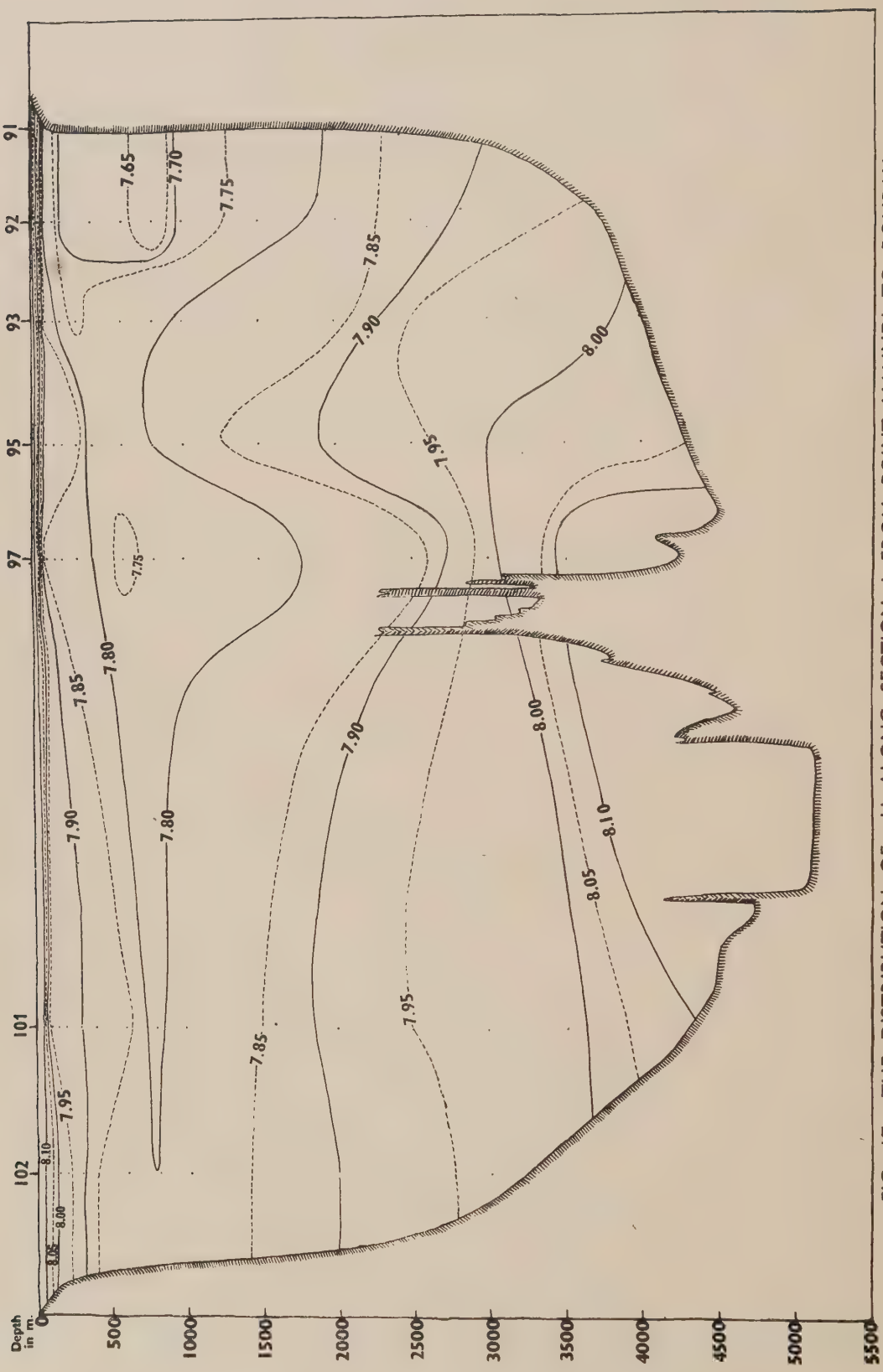

FIG. 17.—THE DISTRIBUTION OF pH ALONG SECTION J FROM POINT MALINDI TO BOMBAY.

The average surface pH is on the whole higher along this section than it is along the other two sections (L and M) which run across the ocean between the Indian and African coasts. The surface pH decreases from east to west, the change following the trend of surface temperature. The thickness of the surface layer decreases in the opposite direction, *i. e.* from west to east. Within the surface layer the isolines are concentrated on the extreme right of the profile off the Indian coast, but are widely spaced on the left-hand side near the African coast. The concentration of the isolines off the Indian coast is a feature in common with the distribution of pH along the sections off the South Arabian coast and in the Gulf of Oman, whereas the widely-spaced isolines near the African coast is similar to what we shall see later in the profile of Section K off the African coast.

Except at the extreme right of the profile there lies below the surface layer and above the minimum pH layer a body of water with pH values (7·85–7·95) which are intermediate between the high values of the surface layer and the low values of the minimum pH layer. This body of water reaches its greatest thickness in the south-western side of the profile, but its thickness diminishes as it passes north-eastwards until it is entirely absent off the Indian coast. Indications of this water were already shown to exist at Stations 39 and 40 on Section H, and we have assumed that this body of water with intermediate values of pH corresponds with the Antarctic intermediate current. Near the African coast it is seen to be continuous with the deep water below it; a similar continuity was already revealed when describing conditions at Station 40. Further north-eastwards the southward flow of the North Indian deep current splits it up into an upper and a lower portion, and we have ventured to speak of these portions as the upper Antarctic intermediate current and the lower Antarctic intermediate current.

The position and thickness of the minimum pH layer varies in this profile from one region to another. It is well-developed off the Indian coast and in the position of Station 97, but is almost non-existent off the African coast. This is a remarkable difference of pH conditions off the two coasts which must have far-reaching effects on the biological conditions. It is in this profile that the minimum pH layer attains its maximum thickness in the whole area of investigation, as it amounts to 1770 m. The upper boundary of this layer (upper 7·80 isoline) lies deepest on the African side of the profile, but rises gradually to only 80 m. below the surface near the Indian coast; its lower boundary (lower 7·80 isoline) is variable in position and lies between 800 and 1875 m. Owing to the upward movement of the lower Antarctic intermediate current in the position of Station 95 the minimum pH layer shows a tendency for division into two branches. The lowest pH values within this layer are found on the Indian side of the profile.

The water beneath the minimum pH layer has again pH values (7·85–7·95) intermediate between those of the low values of the minimum pH layer and the relatively high values of the bottom water, and as it is similar in character to that body of water between the surface layer and the minimum pH layer we feel justified in designating it as the lower Antarctic intermediate current. This water extends as deep as 3000 m. and has a nucleus at about 2000 m. in the south-western basin. The isolines within this water exhibit a prominent hump in the north-eastern basin and a less pronounced one in the south-western basin, a feature which indicates that this deep water wells up as it advances north. Had the line of stations at which pH observations were made been without a gap the actual course of the second hump might have been better defined.

In the deeper water below 3500 m. the pH is relatively high (>8·00) and reaches a value of 8·14 in the vicinity of the bottom in the north-eastern basin and of 8·08 in the south-western basin. As will be shown later, this bottom water comes from the south and presumably is the Antarctic bottom current. But the exceptionally high pH values of this water near the bottom are puzzling, as one would expect water coming from the Antarctic to possess a lower pH on account of its high carbon dioxide content. We should, however, bear in mind the interaction between this water and the floor of the ocean under great pressure. Having a high carbon dioxide content this water would possess a strong solvent action. By its action on the floor of the ocean under great pressure this water

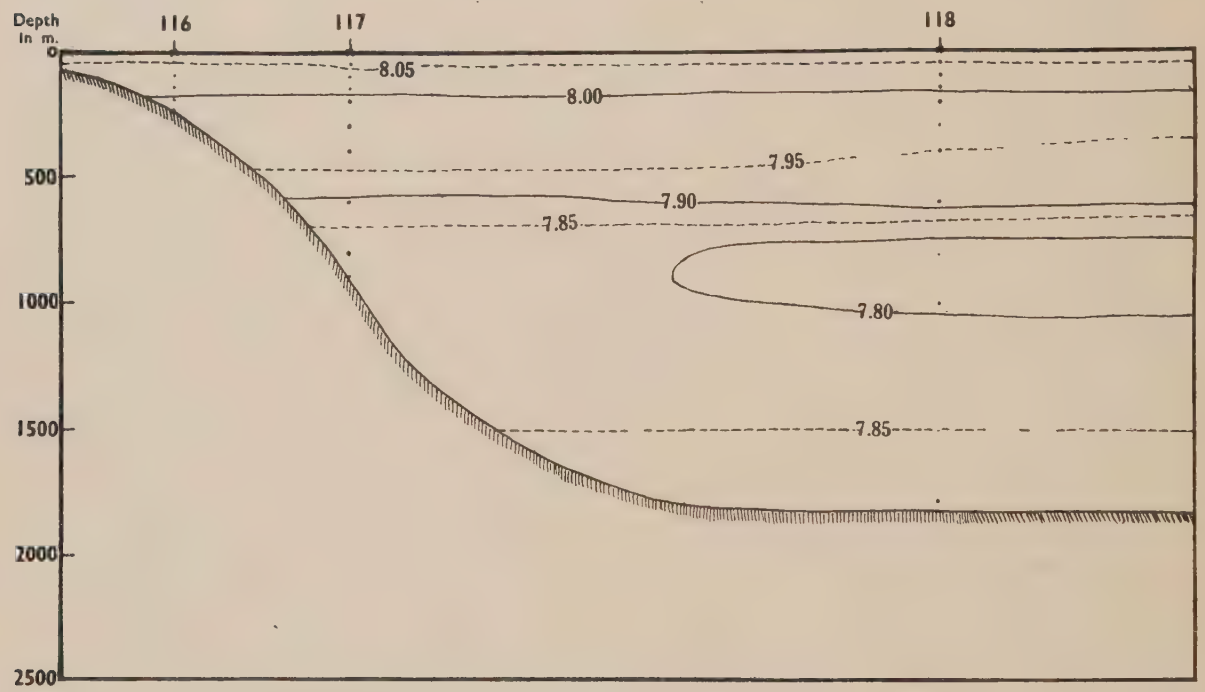

FIG. 18.—THE DISTRIBUTION OF pH ALONG SECTION K OFF THE AFRICAN COAST IN THE VICINITY OF MOMBASA.

reacts on the carbonate constituents of the floor and thus acquires a higher pH. The samples of red clay, known to be of low carbonate content, obtained by the present Expedition at Stations 166 and 167 (Sewell, 1935) in the north-eastern basin, support this suggestion and probably account for the somewhat high pH values of the Antarctic bottom current in this profile.

Section K (*off the African coast*) (Text-fig. 18).—In January pH observations were made at three stations (116, 117 and 118) along Section K, which runs off the eastern African coast in the vicinity of Mombasa. The vertical distribution of pH along this section presents certain marked contrasts to that along the Arabian coast and the Gulf of Oman sections.

The surface layer, the seat of phytoplanktonic activity, is characterized by its great thickness (150 m.) and its high average value of pH, thus indicating a higher phytoplanktonic activity both in magnitude and intensity. The absence of closely-spaced isolines from the surface layer, a feature which was well marked in the sections off the

Arabian coast and in the Gulf of Oman, is very conspicuous. The same feature was already noticed on the African side of Section J.

The minimum pH layer, as defined by values less than 7·80, is much reduced in this profile and appears as a sandwiched band of water only at the seaward station, but is entirely absent at the inner stations. This presents a further marked contrast to conditions off the Arabian coast, in the Gulf of Oman and off the Indian coast, where the minimum pH layer is massive and covers the great depths of the continental slope and shelf.

Between the surface layer and the minimum pH layer there is a massive layer of water with pH values ranging from 7·89 -7·99. Near the African coast this layer is seen to be in continuity with the deep water, a feature which had already manifested itself

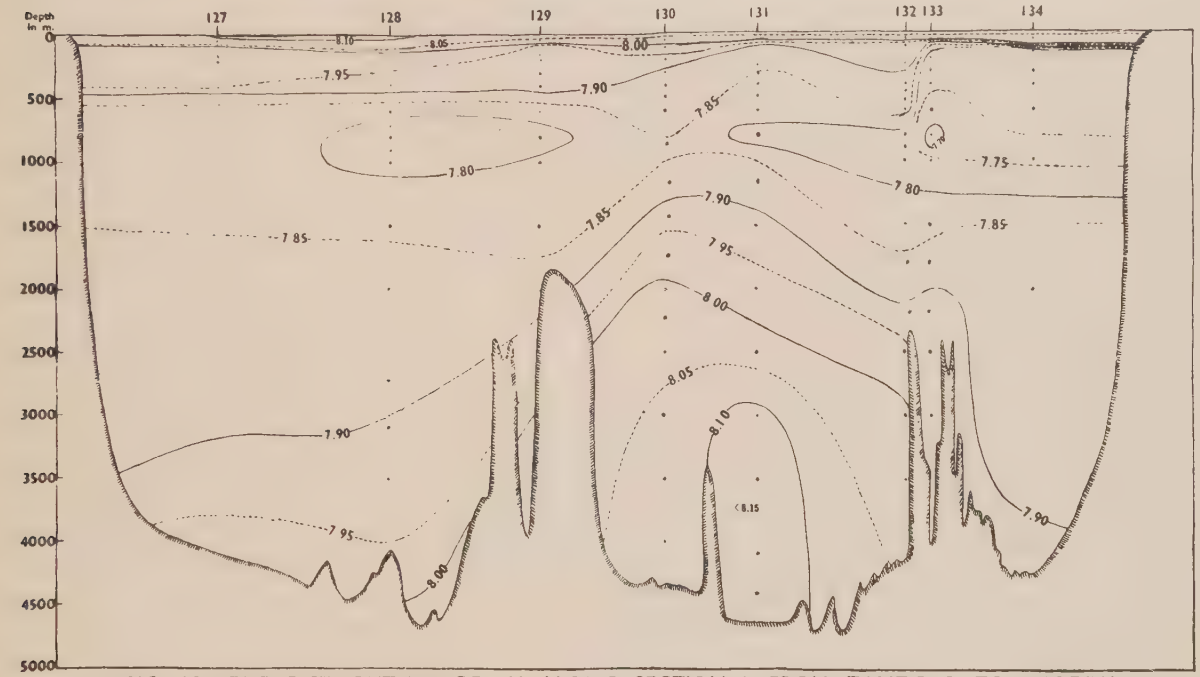

FIG. 19.—THE DISTRIBUTION OF pH ALONG SECTION L FROM ZANZIBAR TO KARDIVA CHANNEL.

off the African coast in Section J. We have already pointed out that this water, with intermediate values of pH, corresponds with the Antarctic intermediate current, but the continuation of this water in the vicinity of the African coast and its splitting into an upper and a lower portion by the intrusion of the North Indian deep current further east justifies our designation of these portions as the upper and lower Antarctic intermediate currents.

The great depths in this profile are filled with water of a comparatively high pH (7·84–7·89) which could, therefore, be described as the lower Antarctic intermediate current.

It is thus seen that we can distinguish from a pH standpoint four water masses in the profile of this section : the surface layer, the upper Antarctic intermediate current, a weak branch of the North Indian deep current and the lower Antarctic intermediate current.

Section L (Text-fig. 19).—Between Zanzibar and Kardiva Channel pH observations were obtained at eight stations (127–134) along Section L during the month of February.

The surface pH decreases from 8·05–8·11 at the surface to a minimum of 7·70–7·85 at a depth of 800–1000 m. The decrease in pH from high values at the surface to lower values downwards is more abrupt at the stations lying on the Indian side of the profile than at the stations lying westwards. The increase in pH below the depth of the minimum value continues with increase of depth to the greatest depth sampled at all stations on this section except at the stations lying between the Seychelles ridge and the Carlsberg ridge (Stations 130 and 131), where the pH decreases again slightly near the bottom.

Except at stations east of the Carlsberg ridge there is a mass of water with intermediate values of pH below the surface layer. Between the African coast and the Seychelles this mass of water has a pH of 7·92–7·99 and extends from a depth of 100 m. to about a depth of 450 m. East of the Seychelles the pH range of this water is lower ; in the position of Station 130 this water extends as deep as 800 m., and in fact seems to be continuous with the deeper water below it. We have already come across a body of water, similar to this in character and similarly situated below the surface layer, which we described as the upper Antarctic intermediate current.

Beneath this water lies the minimum pH layer. The outstanding features of this layer are its great thickness east of the Carlsberg ridge and its absence from the position of Station 130, which gives it a characteristic twofold branching. The thickness of the eastern branch extends from 200 to 1200 m., but that of the western branch is variable and is, on the whole, much smaller. Unfortunately, no hydrographic observations were obtained from depths between 600 m. and 4000 m. at Station 127, but we can safely presume that the minimum pH layer is either much reduced in thickness or is non-existent.

The deeper water underlying the minimum pH layer possesses intermediate values of pH and it seems to well up between the Seychelles and Carlsberg ridges. We have described this water as the lower Antarctic intermediate current.

In the still deeper water the pH gets higher, and although the transition is not sharp these higher values are indicative of another kind of water, namely, the Antarctic bottom current.

Section M (Text-fig. 20).—During April pH observations were obtained between Kardiva Channel and Ras Hafun on the African coast at six stations (166, 167, 169, 170, 171 and 173) along Section M.

The general features of distribution along this section are esesntially the same as along Sections J and L. Below the surface layer we find a stratum of water with intermediate pH values—the upper Antarctic intermediate current. This stratum is much reduced in volume in the positions of Stations 166 and 170. Beneath this stratum is the minimum pH layer—the North Indian deep current—which exhibits a threefold division. Below this layer lies one with intermediate values of pH—the lower Antarctic intermediate current. In the position of Station 167 the isolines within this water show a prominent hump, which is indicative of upwelling. Finally, we find in the great depths in this profile water with relatively higher pH—the Antarctic bottom current.

Horizontal Distribution.

The difference in hydrographical conditions in some regions of our area of investigation during the two monsoon seasons is too great to admit of combining together the observations made in the different seasons. In order, therefore, to avoid the possibility of

misrepresenting the horizontal distribution, we shall confine ourselves, in presenting this distribution, to a consideration of the observations obtained during the months of November–April, which cover well the period of the north-east monsoon in the Arabian Sea and the north-western Indian Ocean. By this arrangement the horizontal distribution of pH over the southern end of the Red Sea and the western end of the Gulf of Aden will be excluded, since observations in these regions were obtained either during September

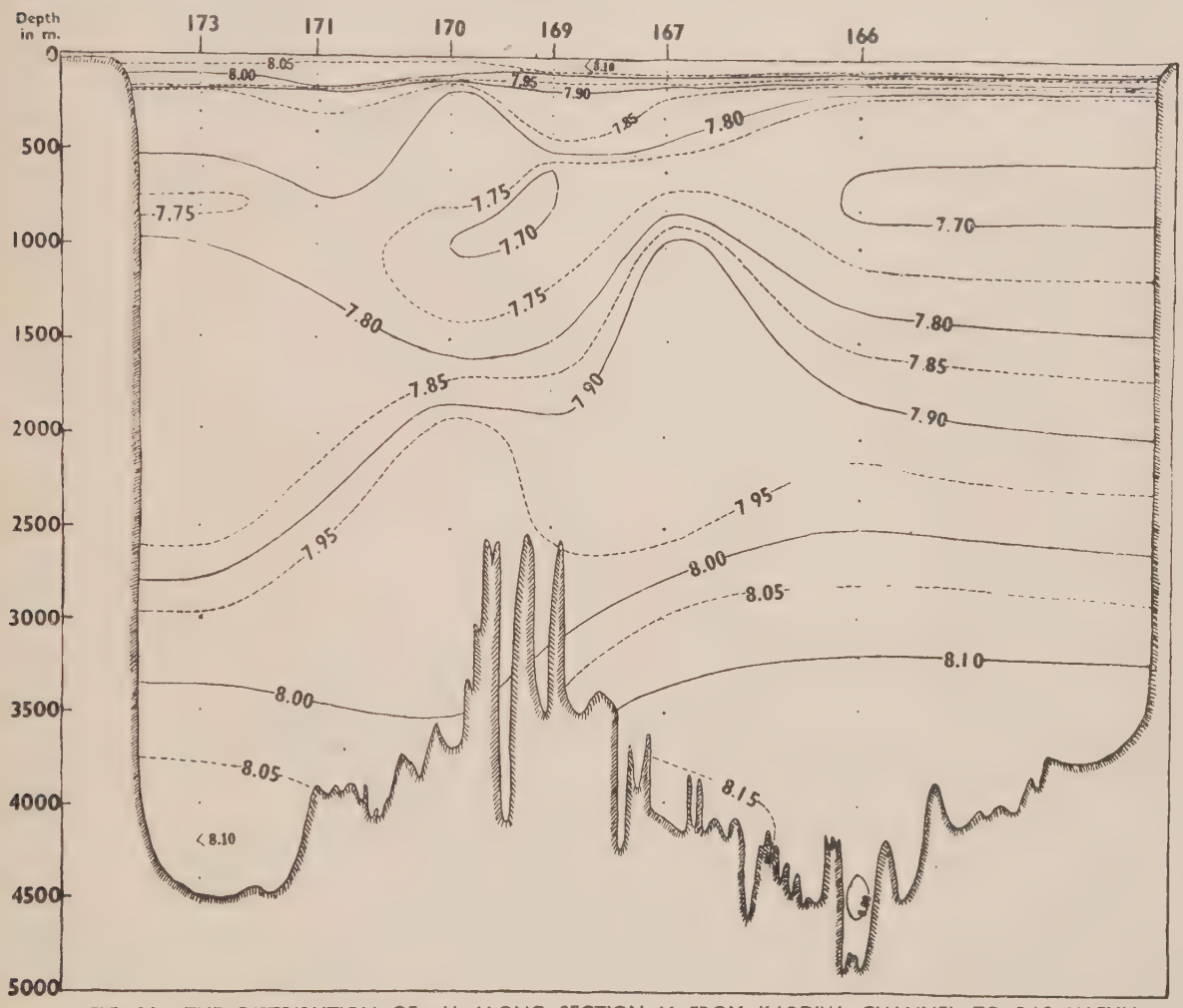

FIG. 20.—THE DISTRIBUTION OF pH ALONG SECTION M FROM KARDIVA CHANNEL TO RAS HAFUN.

or May. Conditions in these regions have been sufficiently elucidated by the description of vertical distribution.

By combining the pH observations obtained during the months of November–April we have constructed charts which show the horizontal distribution of pH at different levels. The isolines are drawn with intervals of 0·05 unit of pH.

Surface.

In any oceanic region the contact of the surface waters with the atmosphere tends to make the surface pH uniform, but the biological activity of the plankton, which proceeds with different intensities at different times, causes irregular variations. The regional

variations of pH at the surface thus become indistinct and the horizontal distribution of pH at the surface, and in fact in the upper 80 metres, does not lend itself to a comprehensive picture of the general conditions. For this reason no charts showing the distribution of pH at the surface or at levels between the surface and 100 m. depth have been given.

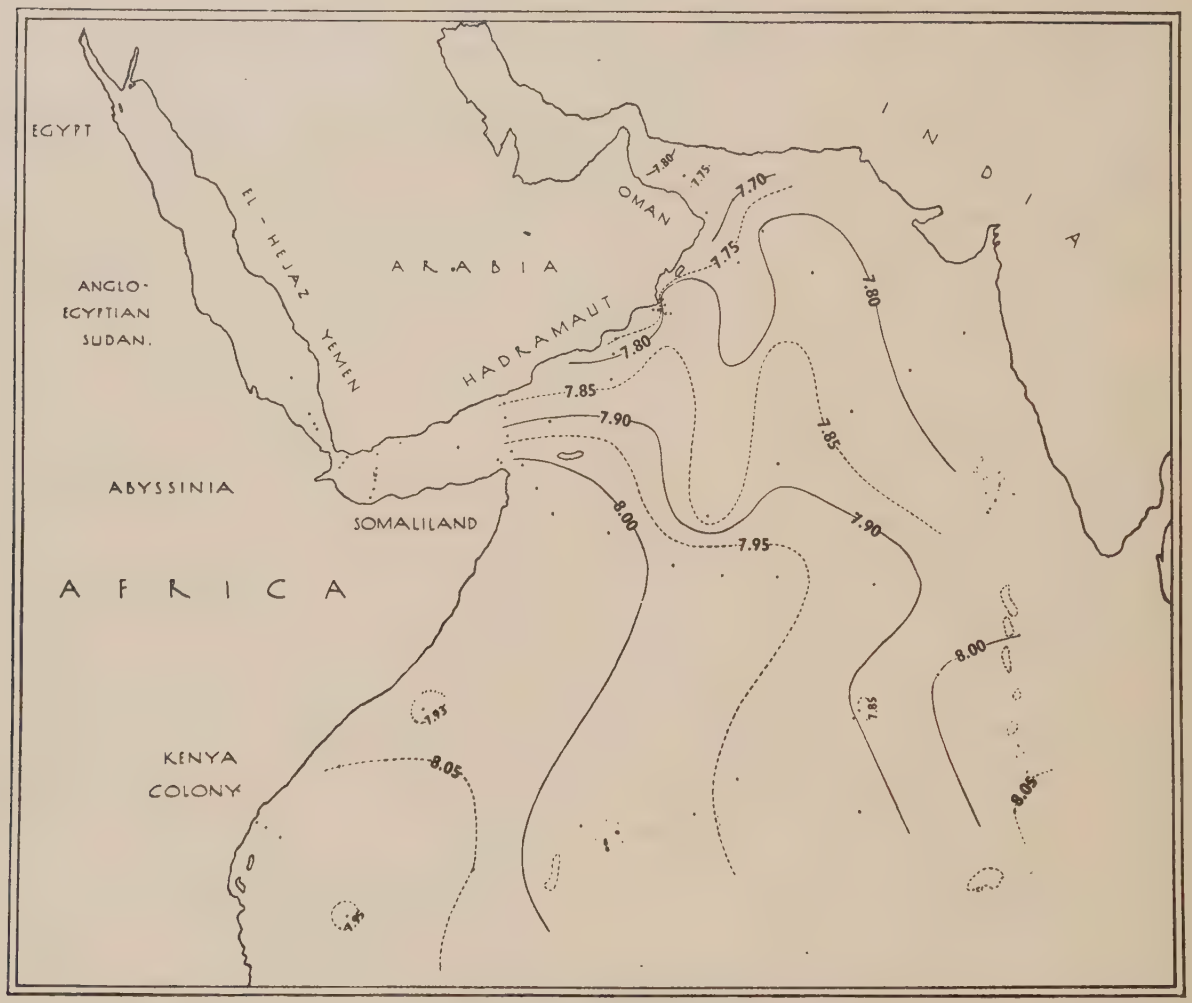

FIG. 21.—HORIZONTAL DISTRIBUTION OF pH AT 100 M.

The surface pH in the area under consideration varies from 8·04 to 8·16. This variation is due chiefly to irregularities in biological activity. The highest surface pH values (8·13–8·16) are found off the South Arabian coast (Stations 51, 52 and 53), off the coast of India (Station 91), and off the African coast (Station 101) ; these high pH values signify an increase of phytoplanktonic activity in these coastal regions. Similar high values occurred in the Central Arabian Sea (Stations 92 and 93).

At 100 *m. Depth* (Text-fig. 21).

Below the surface irregular variations due to biological activity become less and regional variations become more pronounced ; hence the picture of pH distribution at

100 m. depth does not fail to display the regional variations occurring at this depth in spite of certain irregularities produced by the biological activity of organisms.

Low values of pH are found, as shown by the course of the 7·70 and 7·75 isolines, along the southern coast of Arabia. On the other hand, the highest values are found off the African coast and in the region of the Maldives. In the greater part of the area the pH increases in a south-westerly direction and in the Gulf of Oman as we pass up the Gulf.

The chart gives one the impression that water with low pH values originates in the coastal regions of South Arabia and tends to move in a southerly direction, whereas the water with high pH off the African coast, originating obviously further to the south, moves partly in a north-easterly direction and partly in a north to north-easterly direction. As this water meets the south coast of Socotra it is divided and passes partly between Cape Guardafui and Socotra Island and partly east of the island, where it seems to have a component directed towards the south coast of Arabia. The water with high pH in the region of the Maldives is seen to be moving westwards.

When conditions at this level are compared with those at the surface it is revealed that whereas at this level distinctly low values of pH occur off the South Arabian coast, distinctly high values occur at the surface. The cause of this abrupt change from high to low values off this coast finds its explanation in the presence of a well-pronounced thermocline along this coast, and it is possible that the high activity of phytoplankton at or near the surface is connected with increased death and decay at a lower level.

At 200 *m. Depth* (Text-fig. 22).

The general features of pH distribution at this level are similar to those at 100 m.; low pH values occur, as shown by the course of the 7·70 isoline, along the south coast of Arabia and also along the coast of India, whereas high values are found mainly in the south. The pH increases in a southerly direction in the whole area. Passing up into the Gulf of Oman the pH also increases; we have already attributed this increase to an outflowing current from the Persian Gulf.

The expanse of the 7·70 isoline indicates that a greater area is occupied by water of low pH at this level than at 100 m. depth. The chart not only gives the impression that this water originates along the coasts of South Arabia and India, but also indicates that it flows away from its source of origin in southerly and south-westerly directions. This movement is shown by the more southerly positions which the 7·75 and 7·80 isolines now occupy. As the so-called North Indian deep current (see p. 185) is assumed to be formed in the coastal regions of the Arabian Sea and to have a southerly movement, it is justifiable to describe this low pH water itself as the North Indian deep current. As is seen from the chart this current shows a characteristic division into three bands, of which the eastern one, originating along the coast of India, moves in a south-westerly direction, the central band, originating off the South Arabian coast and in the vicinity of Ras el Hadd, moves southwards and the western band takes a south-westerly direction.

The water with high pH, which has apparently originated in the south, shows a corresponding division into three bands.

At the eastern end of the Gulf of Aden to the north of Socotra Island the horizontal gradient is very steep, the pH isolines showing a rapid transition from low to high values owing to the meeting of different water masses.

At 300 *m. Depth* (Text-fig. 23).

At this level the trend and arrangement of pH isolines are similar to those at 200 m. depth. The low pH water is found again along the coasts of South Arabia and India, and the high pH water in the southern region of the area. The pH increases in a south-westerly direction in the open ocean, but increases in a northerly direction in the Gulf of Oman. The more south-westerly position of the 7·85 isoline indicates a stronger influence of the low pH water with increasing depth.

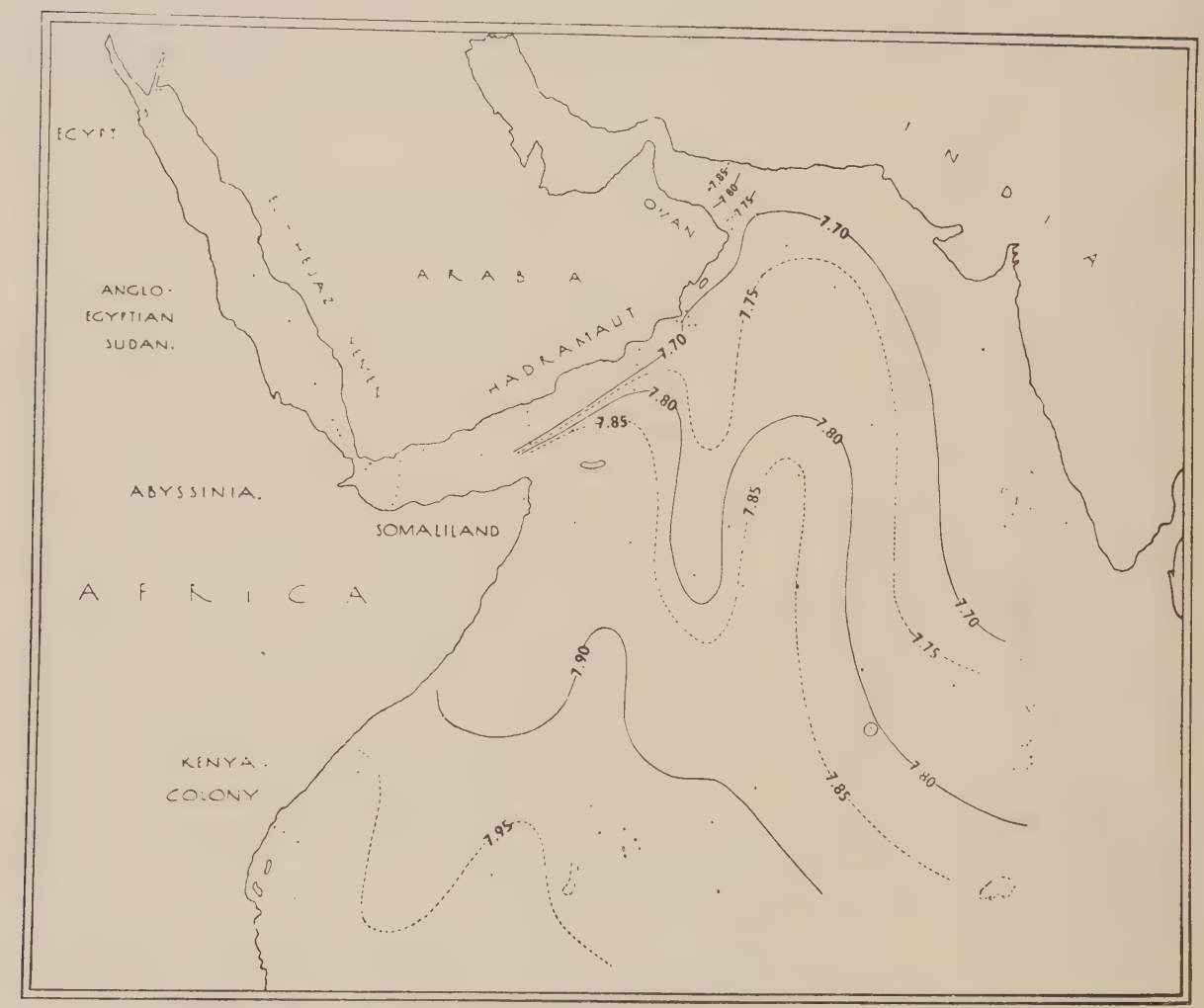

FIG. 22.—HORIZONTAL DISTRIBUTION OF pH AT 200 M.

At 400 *m. Depth* (Text-fig. 24).

The general features of distribution at this level are essentially similar to those at 300 m. The appearance of the 7·65 isoline at this level for the first time gives the picture a new feature. The movement of water with low pH southwards and south-westwards asserts itself more at this level, and on account of this movement the high pH water is confined to the south-western region of the area.

At 600 *m. Depth* (Text-fig. 25).

The most noticeable feature of distribution at this level is the marked predominance of low pH water in the area under consideration. The more southerly position which the 7·80 isoline now occupies indicates that with increase of distance from its principal sources of origin the water with low pH values sinks deeper and disperses into larger areas to the south.

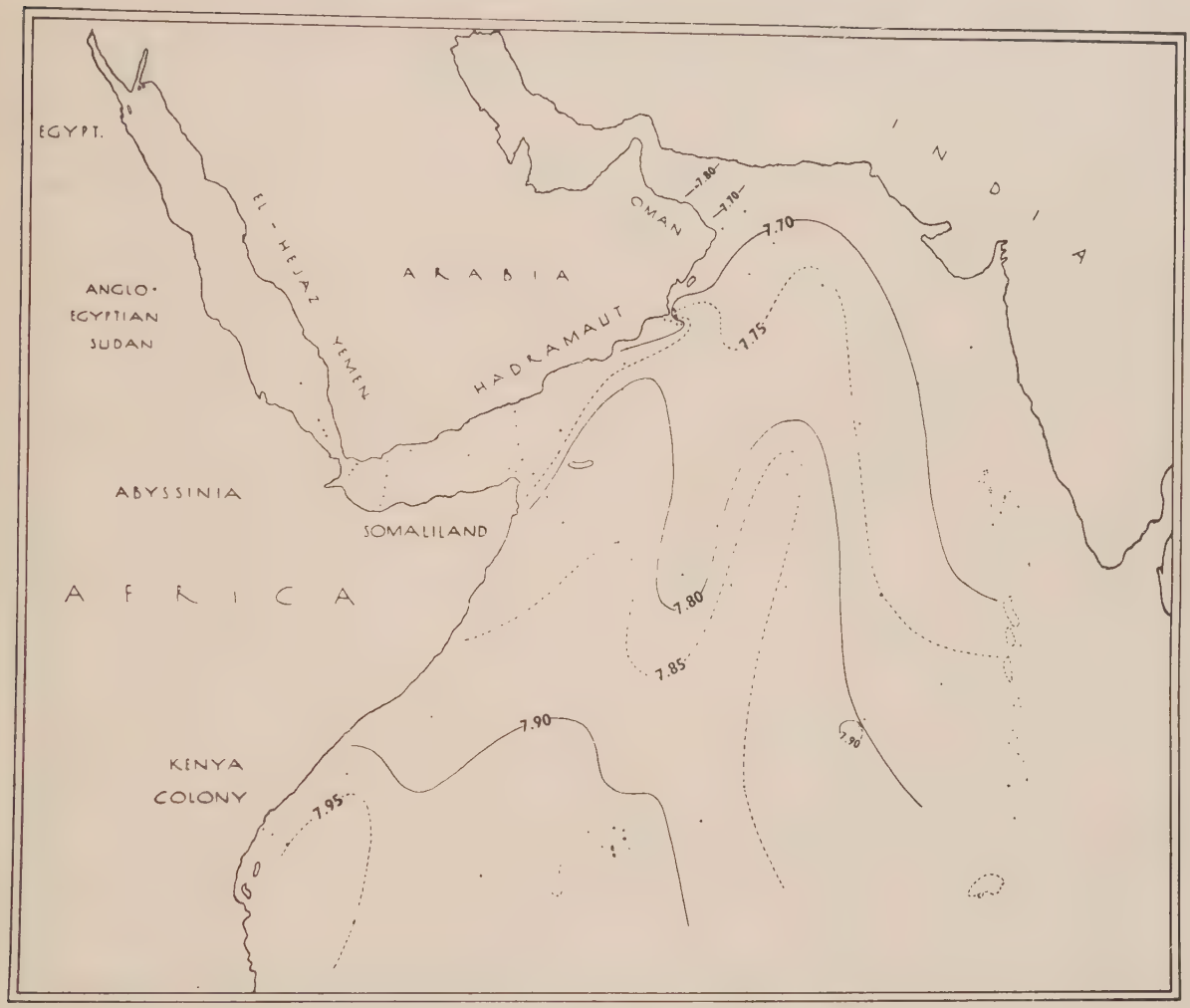

FIG. 23.—HORIZONTAL DISTRIBUTION OF pH AT 300 M.

The high pH water, as represented by the 7·85 and 7·90 isolines, is almost non-existent ; the 7·90 isoline occupies only a small area in the vicinity of Zanzibar, and the 7·85 isoline has also receded to the extreme south of the area.

At 800 *m. Depth* (Text-fig. 26).

The basic feature of distribution at this level is the complete predominance of low pH water in the entire area. In fact we see at this level the climax of the predominance of low pH water and the disappearance of high pH water. It seems that at this level the nucleus of the North Indian deep current is found. Although this current still shows

a division into three bands it is difficult to follow its movement further to the south as it becomes rather diffuse, but there is no doubt that at this level the North Indian deep current has a strong influence on the mass structure of the water.

The 7·65 isoline shows a wider expansion in the Gulf of Oman, along the coast of India and along the South Arabian coast. On the other hand, the 7·90 isoline has completely disappeared from the picture and the 7·85 isoline has receded to the extreme south between the Seychelles and the Carlsberg ridge.

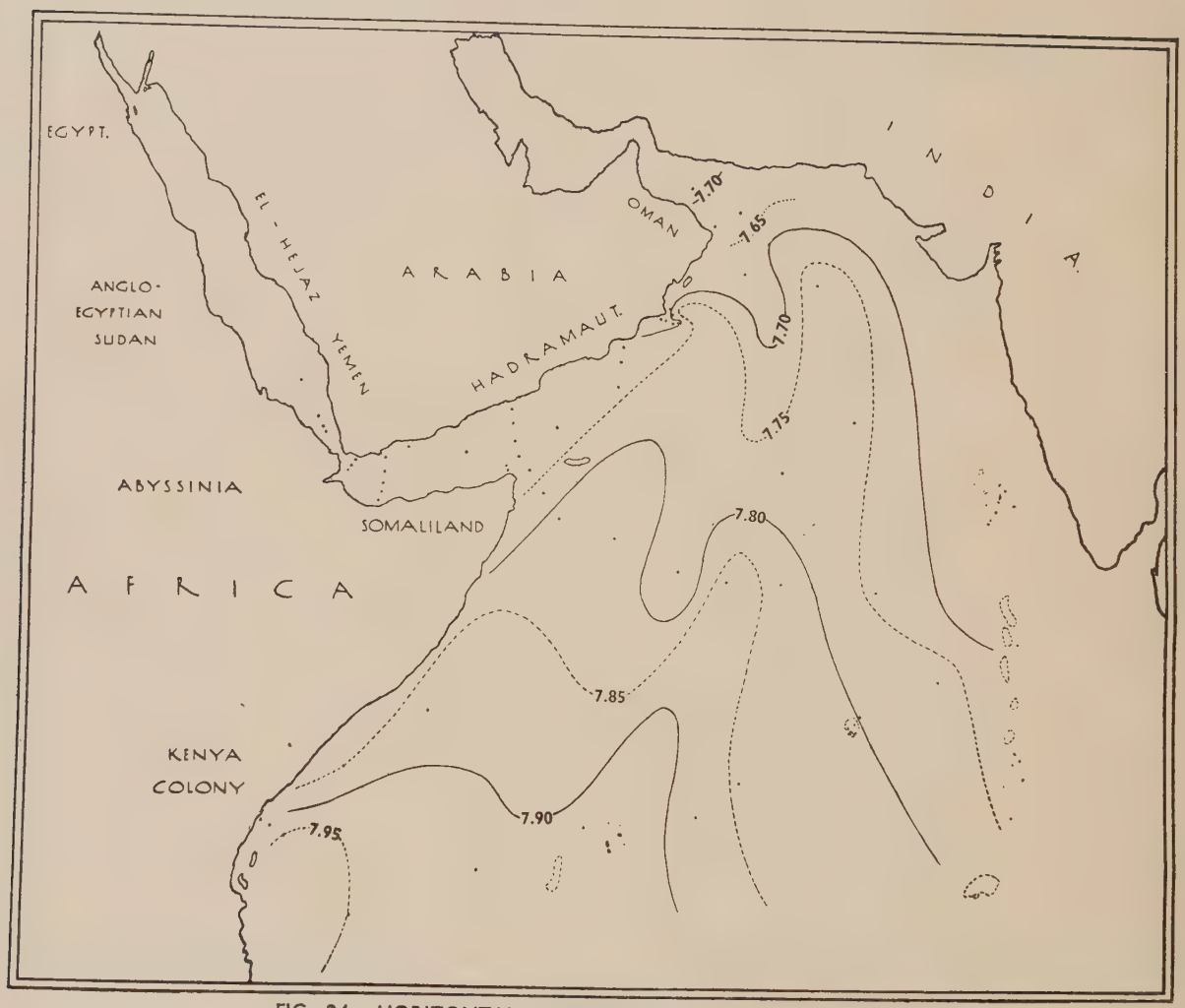

FIG. 24.—HORIZONTAL DISTRIBUTION OF pH AT 400 M.

At 1000 *m. Depth* (Text-fig. 27).

The distribution at this level is essentially similar to that for 800 m., but there are two important points of difference : (1) the entire disappearance of the 7·65 isoline, and (2) the fresh influence which the high pH water regains in the south, as shown by the more northerly position which the 7·80 isoline has now taken.

Considering the 7·80 isoline as representing the boundary between the low pH water from the north and the high pH water from the south, we find that the high pH water is

making a considerable advance to the north not only along the African coast but also in the eastern part of the area. Since this water approaches the area under consideration from the south it can be described, in the light of our knowledge of the circulation in the depths of the Indian Ocean, as the Antarctic intermediate current. We have already seen that similar water is found in varying degrees at the upper levels of 200–600 m., and in order to distinguish the two parts of this current from each other we have suggested designating them as the upper Antarctic intermediate current and the lower Antarctic intermediate current.

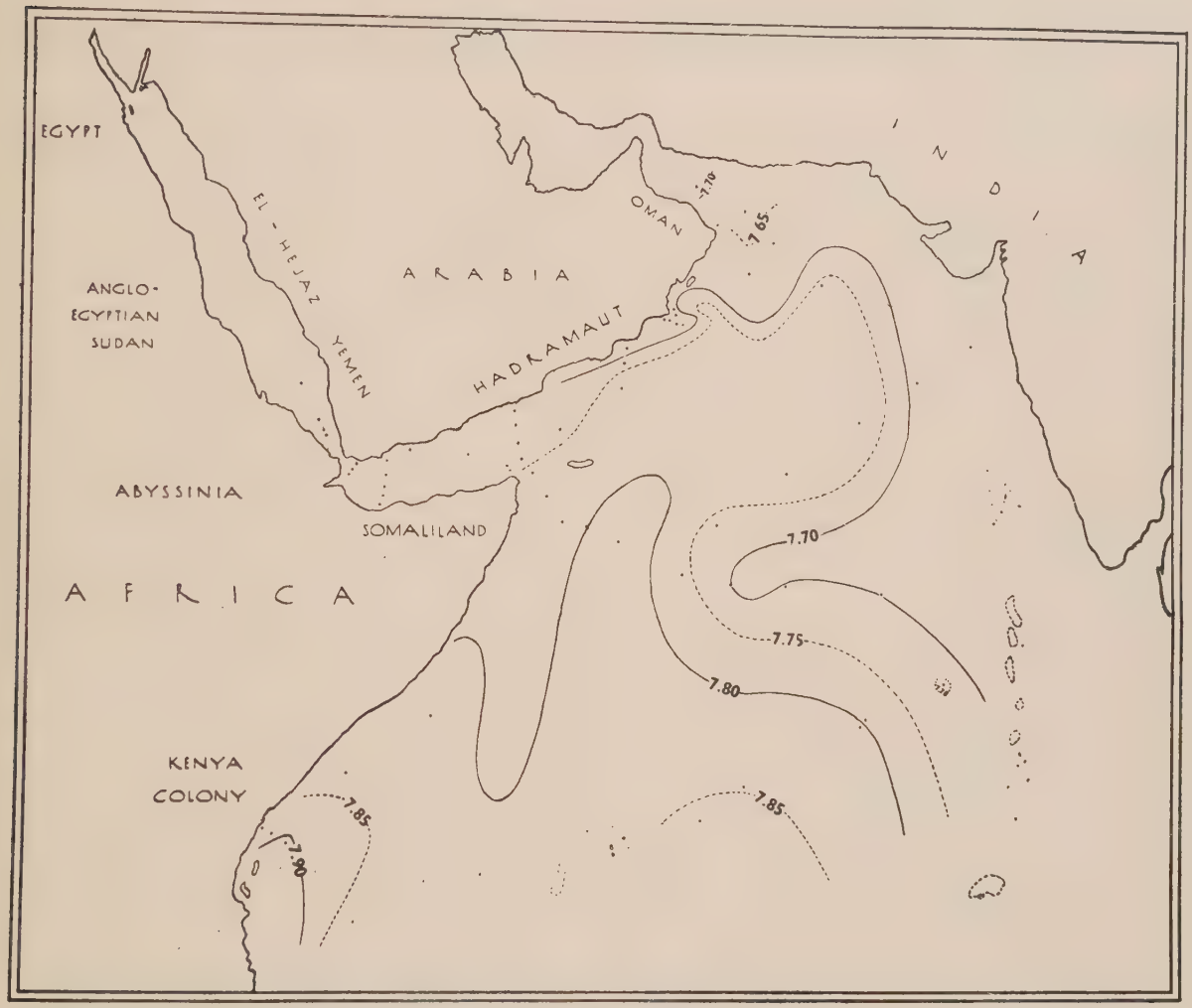

FIG. 25.—HORIZONTAL DISTRIBUTION OF pH AT 600 M.

The bands of the low pH water are seen at this level to have become narrower and to have receded to the north.

At 1500 *m. Depth* (Text-fig. 28).

As is seen in the chart, the water with high pH continues its advance northwards in three tongues. The central tongue, which is more pronounced than the other two, enters between the Seychelles and the Chagos Archipelago and moves in a north-easterly direction; the western one creeps along the African coast and the eastern one passes between the Chagos Archipelago and the Maldives.

The low pH water is now confined to the extreme north-east, although it still has a southern component penetrating between the central and western tongues of the lower Antarctic intermediate current.

At 2000 *m. Depth* (Text-fig. 29).

The most striking feature of distribution at this level is the disappearance of low pH water from the entire area ; the 7·80 isoline is no longer present. The position of the

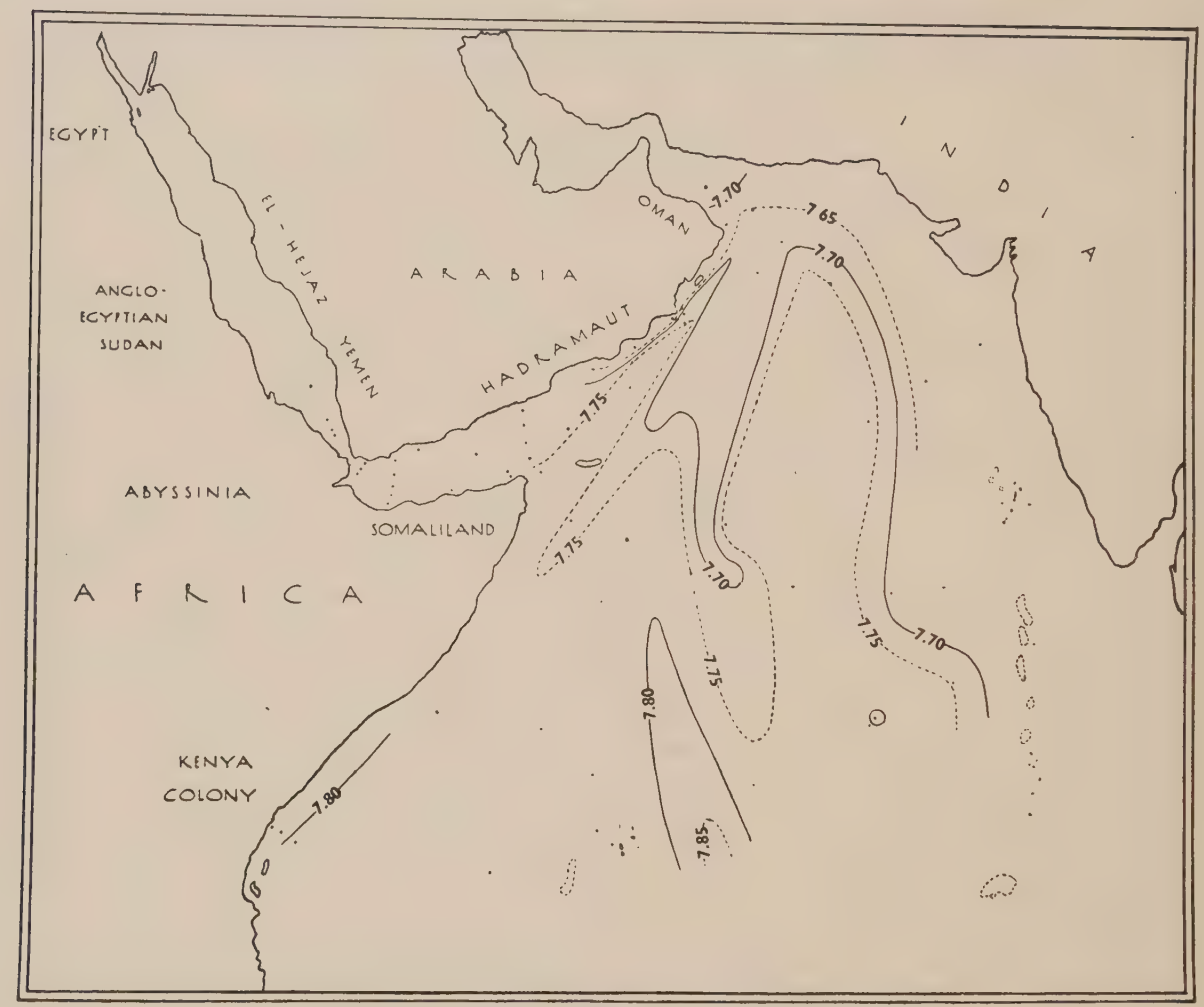

FIG. 26.—HORIZONTAL DISTRIBUTION OF pH AT 800 M.

7·85 isoline shows that the lower Antarctic intermediate current has spread north to the great depths of the Gulf of Oman. The appearance of the 7·95 and 8·00 isolines at this level gives the distribution picture a new feature.

At 2500 *m. Depth* (Text-fig. 30).

The distribution at this level is very similar to that at 2000 m. and calls for but little comment. The 7·90 and 8·00 isolines show a wider expanse to the north than at the previous level. The cause of the very high pH value found at Station 136, lying in the passage

between the Chagos Archipelago and Addu Atoll, is not clear. It is probably related in some way with local interaction with the floor of the ocean.

At 3000 *m. Depth* (Text-fig. 31).

The distribution at this level takes a more definite shape than at the previous level. This is due to a new topographical factor which asserts itself at this level, namely, the Carlsberg ridge which extends between the Chagos Archipelago and Socotra Island.

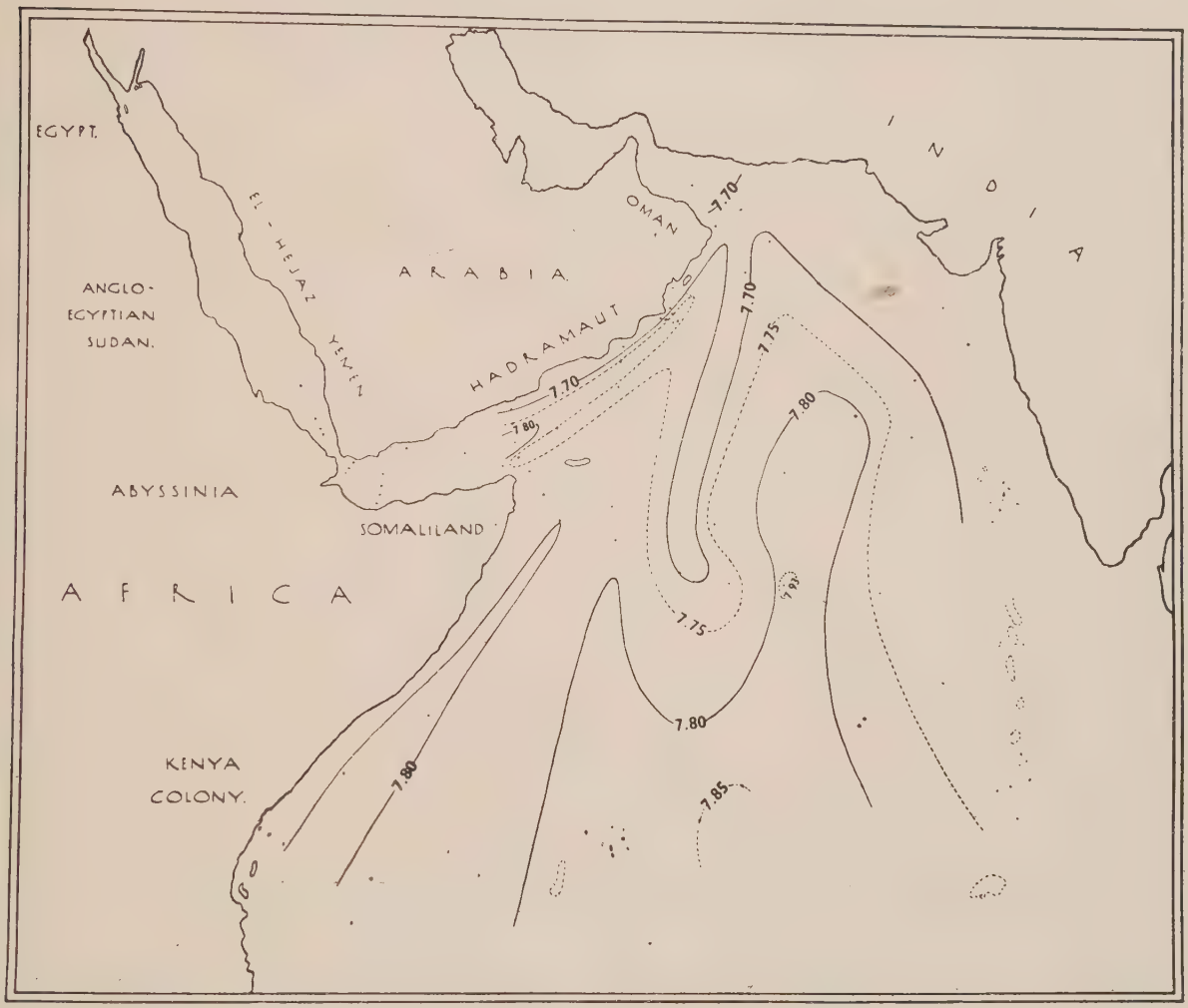

FIG. 27.—HORIZONTAL DISTRIBUTION OF pH AT 1000 M.

The water entering from the south shows a division into three branches. The eastern branch enters east of Carlsberg ridge between Addu Atoll and the Chagos Archipelago, the central one between the Chagos and the Seychelles and the western branch west of the Seychelles. Although there is no sharp transition between the pH values of the water at 2500 m. and the values at this level, the water here can be described, in the light of our knowledge of the deep circulation of the Indian Ocean, as the beginning of the Antarctic bottom current.

In the eastern branch of this current the pH decreases eastwards towards the Indian

coast, which decrease is probably due to admixture with overlying water with lower pH; but its increase in the region of the Arabian basin cannot be explained in the same way, since no water with such high pH values exists in the north. We have already put forward the explanation that the high pH values of this bottom water are acquired locally through interaction with the floor of the ocean. The high pH value found at Station 136 can be

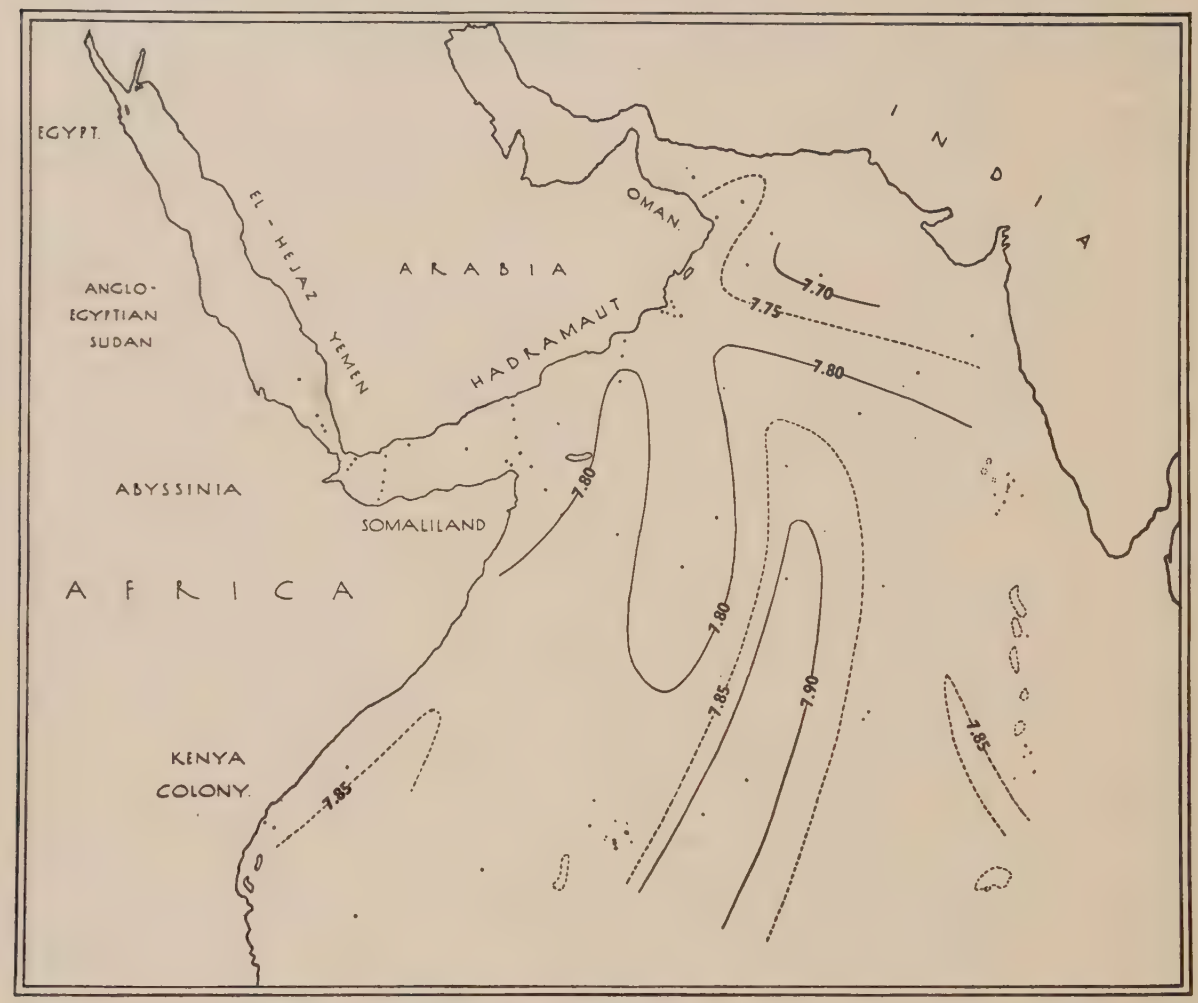

FIG. 28.—HORIZONTAL DISTRIBUTION OF pH AT 1500 M.

explained on similar grounds. The pH of the western branch decreases away from the African coast.

The 7·85 isoline has almost disappeared, but the 7·90 isoline extends north as far as the great depths of the Gulf of Oman.

At 3500 *m. Depth* (Text-fig. 32).*

The main features of distribution at this level are essentially similar to those at 3000 m. depth. The same division of the Antarctic bottom water into three branches is noticeable. The 7·85 isoline has now completely disappeared from the picture.

* In this and the next Text-fig. the bottom contour is drawn to emphasize its relation to the Antarctic bottom current.

At 4000 *m. Depth* (Text-fig. 33).

This is the deepest level at which an appreciable number of observations was made. The water at this great depth shows the same threefold division revealed at 3000 and 3500 m. levels. The isolines have lost their stream-like character and it seems that there is little or no appreciable movement at this level. Only water with pH values higher than 7·95 is found at this depth, and the pH within each branch decreases eastwards.

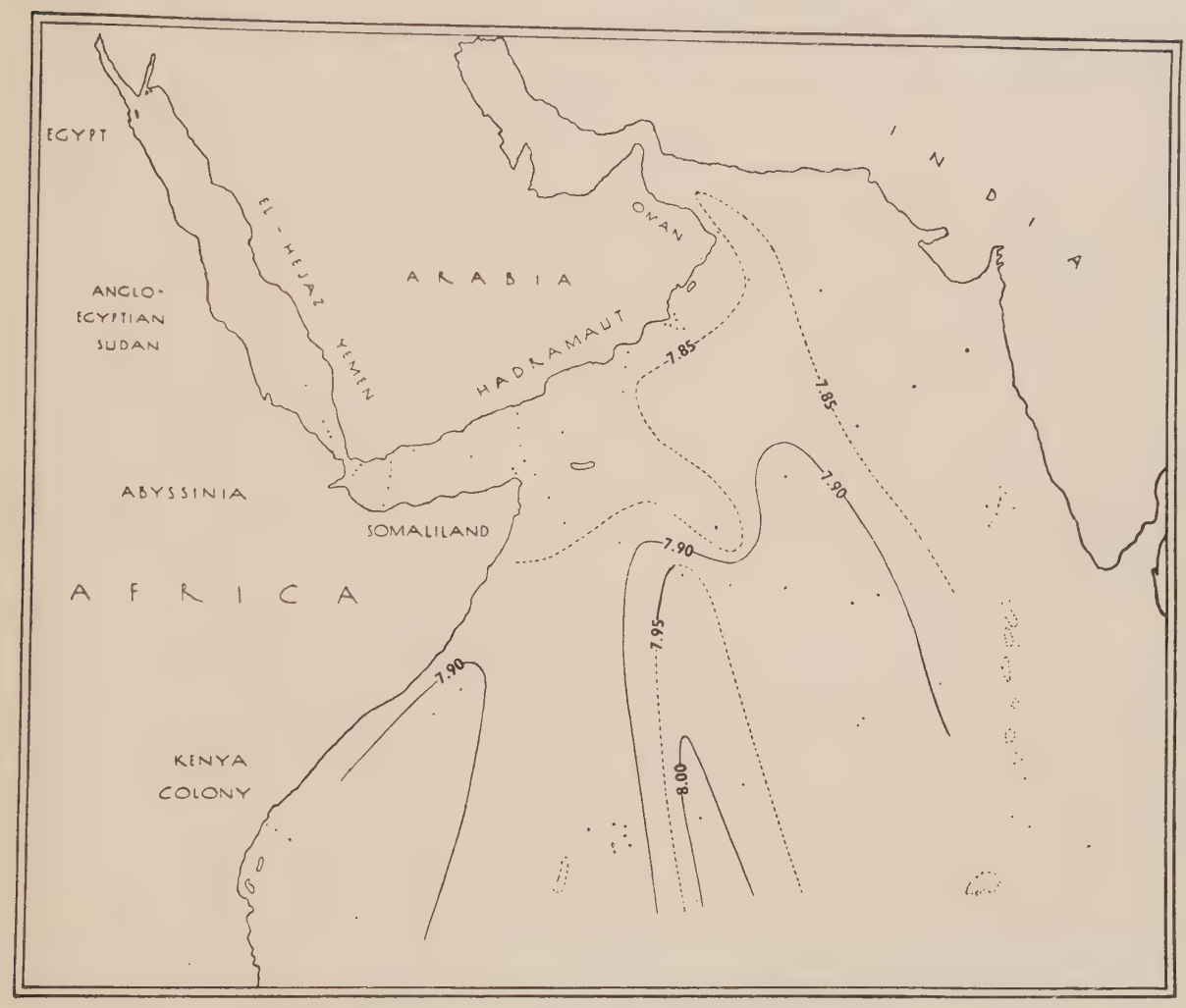

FIG. 29.—HORIZONTAL DISTRIBUTION OF pH AT 2000 M

SHORT-PERIOD VARIATIONS OF pH.

The problem of vertical oscillations in the ocean has become of general interest in oceanography. The earlier investigations of Helland-Hansen and Nansen (1909) in the North Polar basin and the Norwegian Sea indicated that considerable vertical oscillations of the water-layers occur in the sea and that an occasional vertical series of oceanographical observations cannot therefore be taken as representative of the average conditions at any particular station. Later the same authors (Helland-Hansen and Nansen, 1926) discussed the problem anew and concluded that these vertical oscillations are probably connected

with the tides, strong evidence being found for 12-hour (lunar) and 24-hour periods. It was further discussed by Helland-Hansen (1930), by Defant (1932) and by several other investigators.

Bearing in mind that pH observations could not be expected to throw much light on this problem of vertical oscillations owing to irregularities caused by varying intensities of biological activity in the upper strata, which are partly the seat of these vertical oscilla-

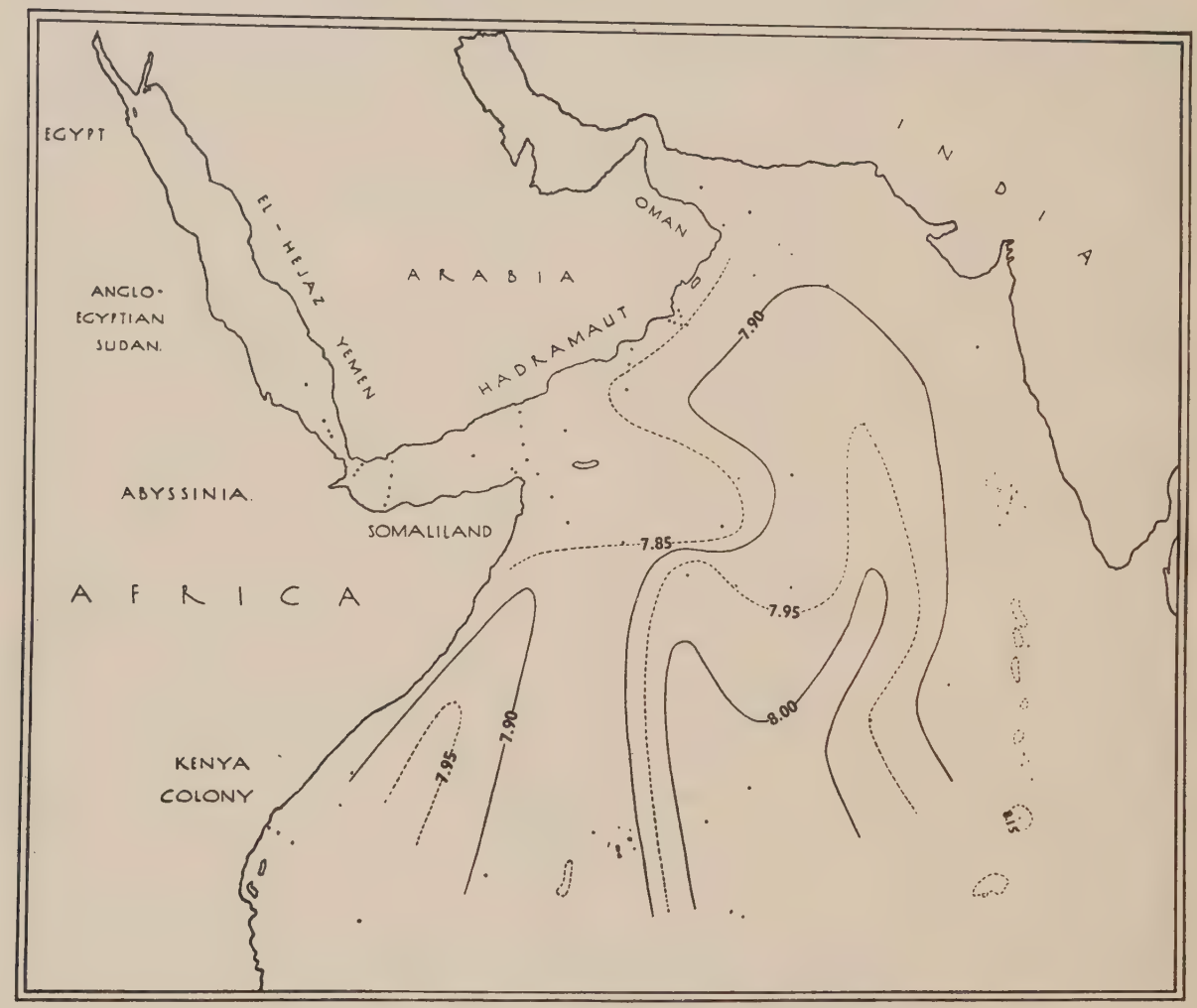

FIG. 30.—HORIZONTAL DISTRIBUTION OF pH AT 2500 M.

tions, short-period observations of pH were made with the sole object of finding how far these vertical oscillations are displayed by pH observations.

For this purpose observations of pH were obtained at intervals of roughly six hours at three stations in our area of investigation over periods varying from 12 to 24 hours. At Station 97 the period of observations extended over 18 hours, during which four series of observations were obtained at the usual depths from the surface down to a depth of 800 m.; the observations thus obtained are recorded under Stations 97A–97D. Owing to a mishap at Station 97D observations were, however, obtained down to a depth of 150 m. only. At Station 131 the period of observations extended over 24 hours, during which five similar series were made and the observations so obtained are recorded under Stations

131A–131E. At Station 145, which lies in Kardiva Channel, the period of observations extended over 12 hours, during which three series of observations were taken from the surface down to a depth of 400 m. only, the observations being recorded under Station 145A–145C.

To illustrate the nature of the short-period variations of pH, only observations obtained at Station 131 will be considered, as they extended over a relatively longer period. The pH observations at the depths of 0, 50, 100, 150, 200, 300, 400, 600 and 800 m. are plotted against time in Text-fig. 34.

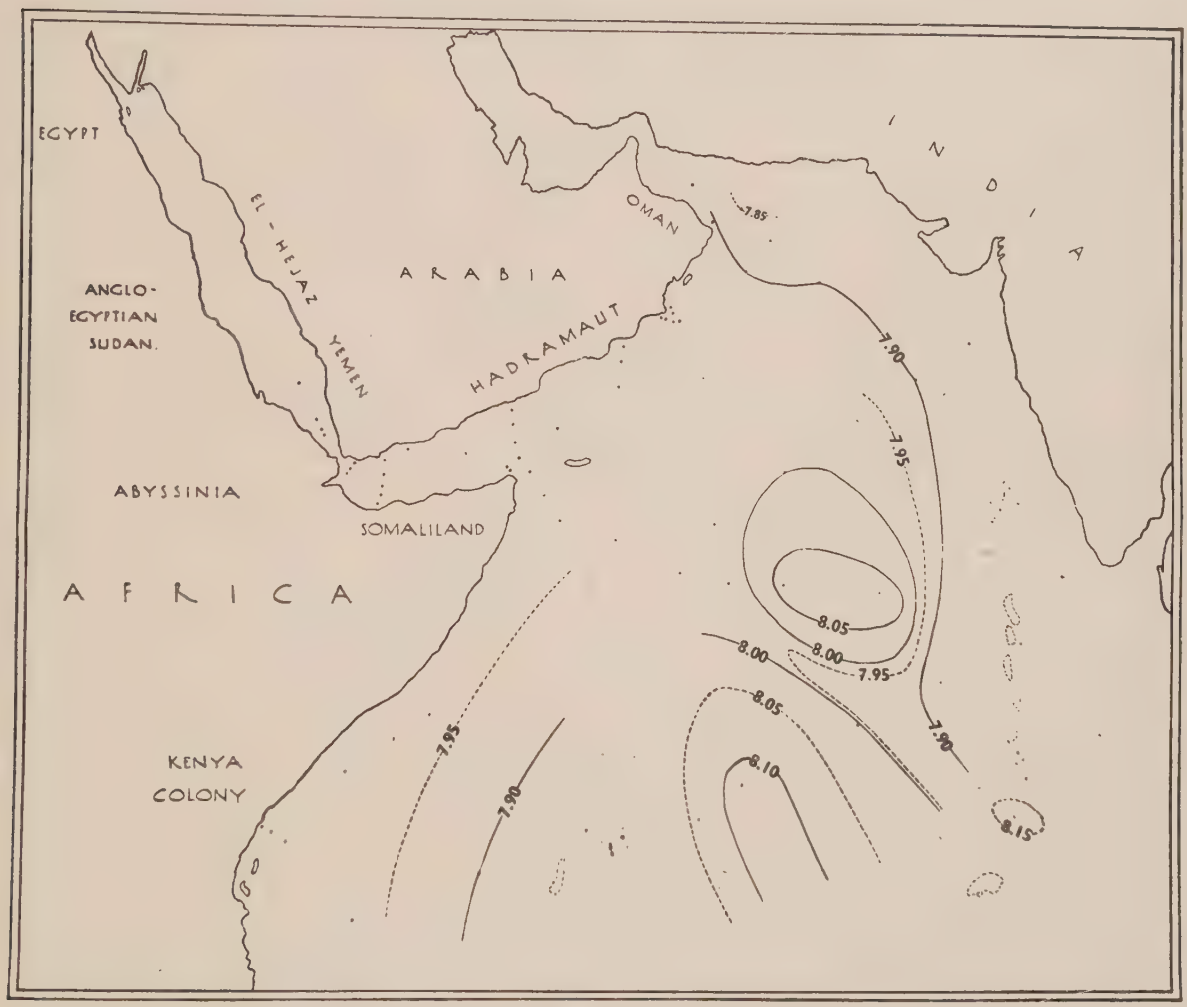

FIG. 31.—HORIZONTAL DISTRIBUTION OF pH AT 3000 M.

A satisfactory study of the short-period variations of pH is not possible on the basis of the present observations since they suffer from two drawbacks. In the first place they were carried out from the ship adrift, and secondly no special effort was taken to secure observations from the same depth at equal intervals of time. The curves represented in Text-fig. 34 show, however, that a considerable variation of pH takes place during the course of 24 hours.

The curves for the surface 50 and 100 m. depths show a steady increase in pH during the day time and a similar decrease during the night time. This is to be expected in the upper levels on account of photosynthetic activity during the day time, which causes the

pH to rise ; during the night time there would be an opposite effect. The curves for 150, 200, 300, 400 and 800 m. depths show similar features, which suggest a periodic character of these time variations of pH. The curve for 600 m. shows, however, at the time of observation at Station 131A a distortion, the cause of which is not clear or else it may be attributed to a horizontal displacement of the water-layers.

In view of these short-period variations of pH, the question now arises as to the representative quality of the serial observations of pH (and other serial oceanographic

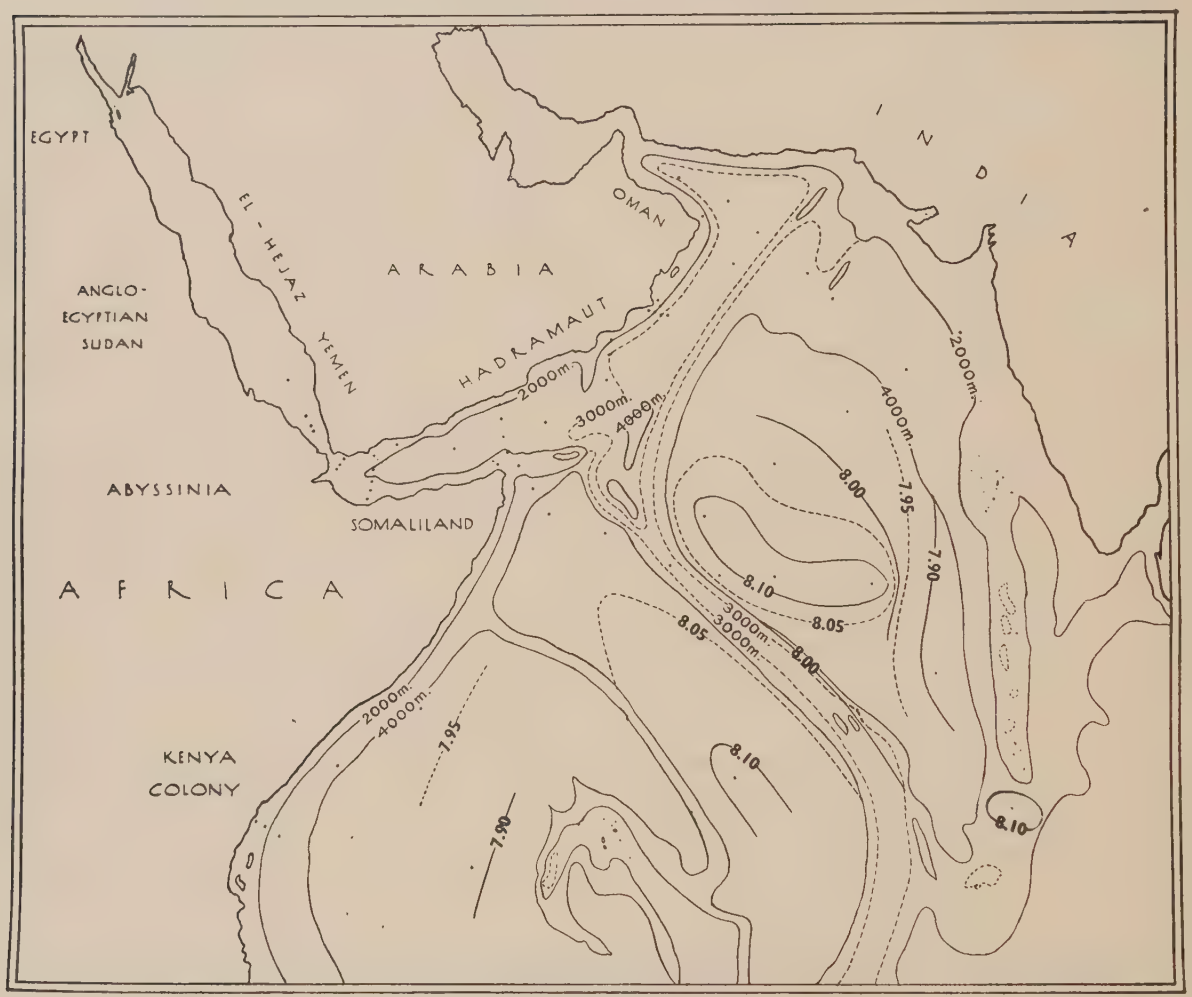

FIG. 32.—HORIZONTAL DISTRIBUTION OF pH. AT 3500 M.

observations as well) and the significance of the conclusions derived therefrom. When the curves represented in Text-fig. 34 are examined, it is found that the maximum pH difference at any depth during the course of 24 hours does not exceed 0·10 pH unit. And since, in the construction of the vertical profiles and charts of horizontal distribution of pH, isolines were drawn at intervals of 0·05 pH unit and since the use of an interval of 0·10 pH unit would not have radically altered the pictures shown in the various profiles and charts, we can safely conclude that although the short-period variations of pH in the sea are startling, they would not affect to any considerable degree the significance of the conclusions which we have derived from the pH distributions.

DISCUSSION.

In this section an attempt will be made to obtain, from our description of vertical and horizontal distributions, an insight into the general features of the hydrography of the north-western Indian Ocean and its adjoining waters and to interpret certain biological

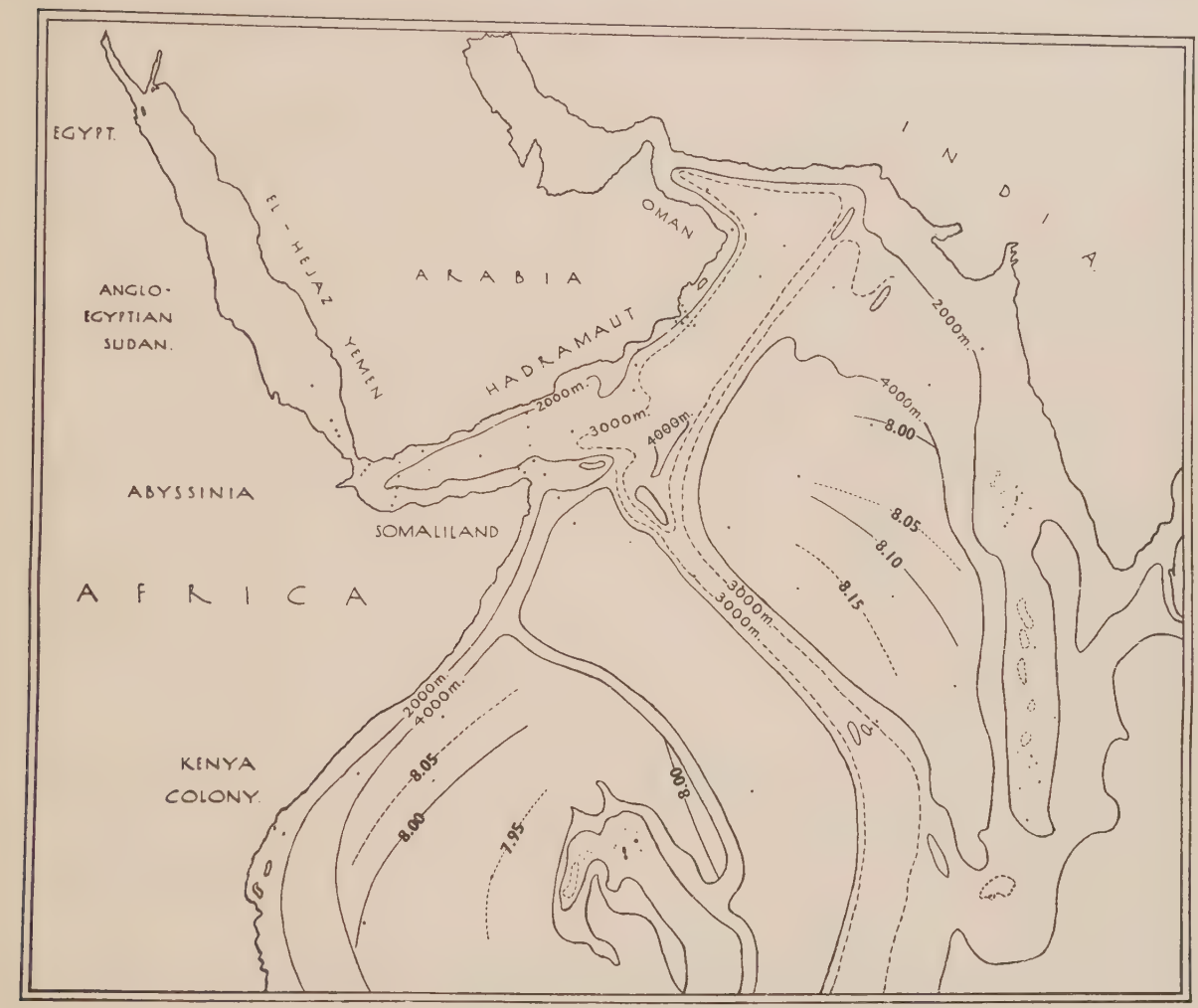

FIG. 33.—HORIZONTAL DISTRIBUTION OF pH AT 4000 M.

phenomena. As such an attempt would involve a reference to the general circulation of the Indian Ocean and its adjoining gulfs, we shall begin with a brief outline of our present-day knowledge of this circulation in so far as it has a close bearing on our area of investigation.

Historical Review of the Circulation of the Indian Ocean.

Water Movements in the Straits of Bab-el-Mandeb.

The Red Sea is connected with the Gulf of Aden by the Straits of Bab-el-Mandeb; these Straits are 14 miles wide between Ras Bab-el-Mandeb and Ras Siyan and are divided by Perim Island into Large Strait and Small Strait. The deep part of the Red Sea is

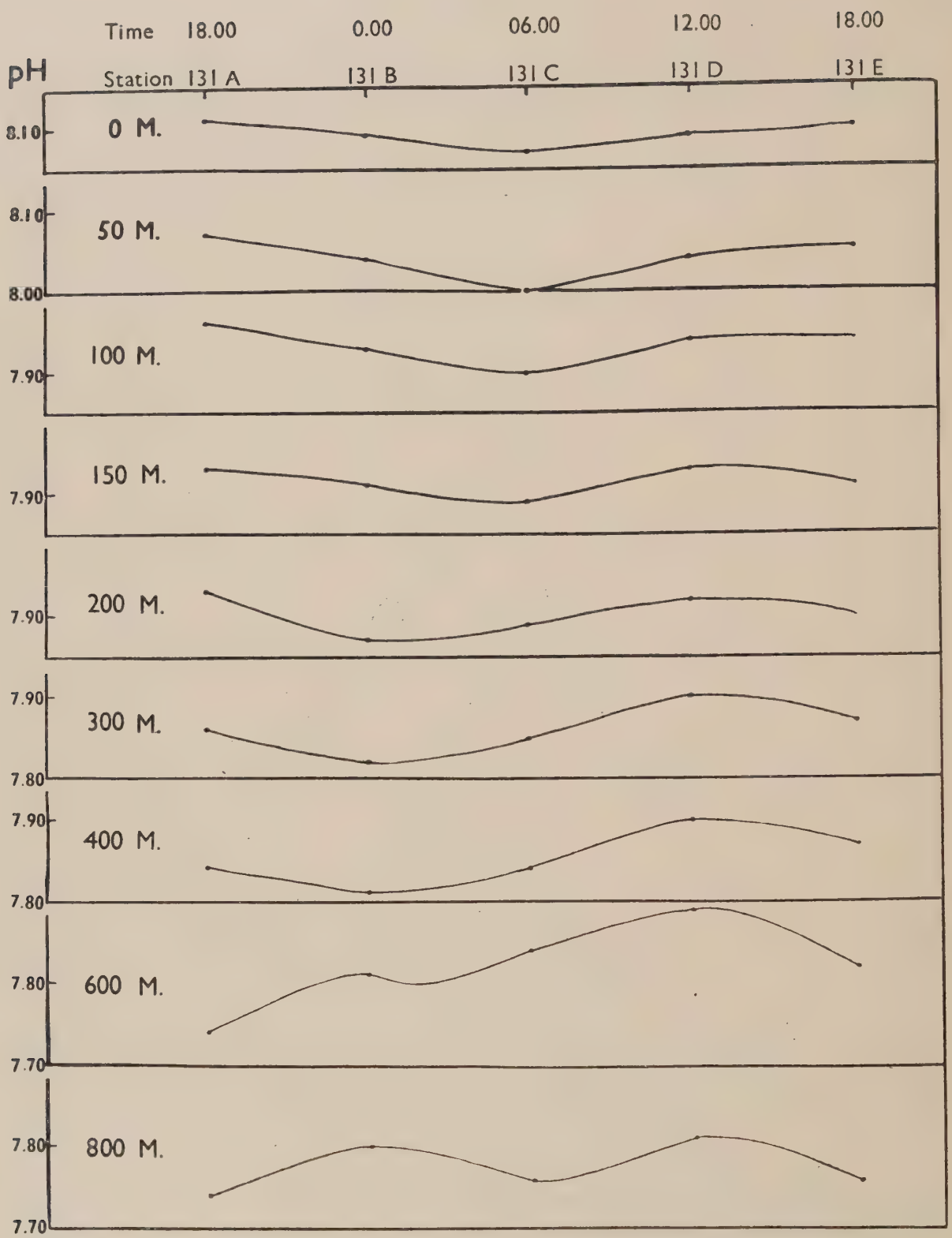

FIG. 34.—TIME VARIATION OF pH FOR VARIOUS DEPTHS AT STATION 131.

separated from the Gulf of Aden by a submarine threshold about 100 m. deep near Great Hanish Island.

The observations of salinity in the Straits of Bab-el-Mandeb made by Makaroff (1894) in the "Vitiaz" in March, 1889, constitute the first indication of the outflow of Red Sea water into the Gulf of Aden. He found that whereas the surface waters in the Straits had a salinity of 36·1–36·5°/$_{oo}$, the deep water at a depth of 150 and 250 m. had a salinity of 37·4 and 38·13°/$_{oo}$ respectively.

The first attempt at a direct study of the water movements in the Straits of Bab-el-Mandeb was, however, made in 1890 by Capt. Usborne Moore in H.M.S. "Penguin" by means of a somewhat crude current meter (Wharton, 1898). Although the results showed that the lower strata did not run in the same direction as the surface strata, they were too ambiguous to afford more definite information.

The water exchange through the Straits of Bab-el-Mandeb was further shown by the salinity and temperature observations of the "Pola" in 1897–1898. Luksch (1898, 1901) concluded from these observations that light water flows from the Indian Ocean into the Red Sea along the Arabian side of the Strait and that more saline water flows out of the Red Sea through the western Strait at its great depths.

In January, 1898, Commander H. J. Gedge (1898) carried out successfully a series of current measurements in the Large Strait of Bab-el-Mandeb from H.M.S. "Stork". He used for his measurements a Pilsbury current meter, which had been improved after a series of experiments made by Capt. Usborne Moore in the English and Faroe Channels. On January 19th, 1898, the "Stork" was anchored in a depth of 215 m. about 7 miles S.W. by W. from Perim Island (12° 34′ 45″ N., 43° 17′ 45″ E.), and repeated observations were made during daylight for four days. Measurements were made at the surface, 9, 44, 91, 137 and 192 m. depths. As a result of these measurements the following conclusions were drawn: During the period of observation there was a permanent current at the surface setting into the Red Sea. At a depth of 192 m. there was a permanent current setting outwards at probably the same speed; both currents were influenced by the tidal streams. The dividing line between these two permanent currents was at a depth of 137 m., but the observations did not last long enough to define the position of this line with any precision.

The more recent Italian oceanographic exploration of the Red Sea has added considerably to our knowledge of the water movements in the Straits of Bab-el-Mandeb. In 1923–1924 extensive current measurements in the Straits of Bab-el-Mandeb were carried out from the surveying ship "Amiraglio Magnaghi" and from the vessel "Generale Arimondi". These measurements were made both in the Large Strait and in the Small Strait at a series of stations and their duration varied at different stations. For instance, at one station in the Large Strait measurements extended over a period of 14 days and at another station they lasted for about 8 hours only.

From his study of these current measurements, Vercelli (1925) came to the following conclusions: During the winter monsoon period there flows at the surface a current northwards from the Gulf of Aden into the Red Sea through the Straits of Bab-le-Mandeb. With increasing depth the direction remains the same, but the speed decreases until it reaches *nil* at about 100 m. Below this depth the current runs in the opposite direction, *i. e.* flows out of the Red Sea into the Gulf of Aden. The speed of this current increases with increasing depth until it reaches in the vicinity of the bottom values as high as those

of the north-going current at the surface. Both these currents are modified by the ebb and flow of the tide. Vercelli also reported that in the Large Strait temporary vertical oscillations take place in the transitional layer, *i. e.* in the layer between the Gulf of Aden surface current and the deep Red Sea current, and that these give rise to periodical variations in the temperature and salinity observable in the transitional layer. These thermo-haline oscillations were found to be connected with the rhythm of the tide, as has been found elsewhere (see, for example, Jacobsen and Thomsen, 1934).

The temperature and salinity observations of the " Amiraglio Magnaghi " in the Straits of Bab-el-Mandeb in 1923–1924 also bear out the existence of a deep Red Sea current flowing out of the Red Sea into the Gulf of Aden and a surface current flowing in the opposite direction (Vercelli, 1927).

In the spring of 1927 H.M.S. " Ormonde " made a line of five stations, running from the Straits of Bab-el-Mandeb into the Gulf of Aden, where temperature and salinity observations were taken. These observations proved (Matthews, 1927) the existence of the Red Sea outflow at all stations.

Schott (1929) summarized the results of oceanographical research in the Straits of Bab-el-Mandeb and concluded that the results establish the existence, along with the surface current which flows for the greater part of the year through the Straits of Bab-el-Mandeb to replace the loss by evaporation in the Red Sea, of a second deep current flowing in the opposite direction into the Gulf of Aden.

In 1929 further Italian investigations were carried out in the Red Sea on board the " Amiraglio Magnaghi " with the participation of the vessels " Lepanto " and " Porto Corsini ". These investigations included current measurements in the vicinity of the Straits of Bab-el-Mandeb during the month of July. From these investigations Vercelli (1931) concluded that during the summer season there pass through the Straits of Bab-el-Mandeb three currents : A surface current (0–30 m.) from the Red Sea into the Gulf of Aden, a mid-current (40–150 m.) from the Gulf of Aden into the Red Sea, and finally a deep current (150 m. to the bottom) from the Red Sea into the Gulf of Aden.

Van Riel (1932) published some serial observations of temperature, salinity and oxygen which were taken by the " Snellius " in the southern Red Sea and the Gulf of Aden in April, 1929. These observations provide also valuable evidence of the outflow of the deep Red Sea water into the Gulf of Aden.

In a preliminary treatment of the temperature and halogen content observations of the present Expedition, Sewell (1934) pointed out that in September the water movements in the Straits of Bab-el-Mandeb differ from the results obtained by the " Amiraglio Magnaghi " in 1924, and the " Ormonde " in 1927 in the months of April and May. There were indications of at least three different strata of water in the Straits : A surface layer flowing out of the Red Sea into the Gulf of Aden ; a mid-stratum, by far the largest of the three strata, flowing into the Red Sea between the depths of 70 m. and 160 m. ; and a lower stratum, consisting of the bottom water of the Red Sea, which was small and scarcely passed over the sill. Sewell further showed that the observations in May agree with those of the " Amiraglio Magnaghi " and " Ormonde ". It seems that at the time when Sewell published his preliminary notes he was not aware of the Italian investigations in July, 1929.

Gulf of Aden.

Information on the surface currents in the Gulf of Aden is amply given by the work of Matthews (1926) who discussed these currents in his report on the hydrographic observations made by H.M.S. " Sealark " and by ships trading in the Indian Ocean. But our knowledge of the deep currents in the Gulf, especially at its eastern end, was scanty prior to the John Murray Expedition.

The observation of a warm, highly saline deep current flowing out of the Red Sea into the Gulf was made in the past by the " Vitiaz ", " Valdivia ", " Pola " and " Stork ", as we have already pointed out. New observations were made in the Gulf in 1924 by the "Amiraglio Magnaghi" (Vercelli, 1927) and in 1927 by H.M S. " Ormonde " (Matthews, 1927). These observations confirmed the outflow from the Red Sea of a deep current which could be detected eastwards as far as the middle of the Gulf.

When Rafael de Buen (1927) expressed the surprising view that no Mediterranean water passes through the Straits of Gibraltar westwards into the Atlantic Ocean and that the Mediterranean deep current bends upwards at the sill and turns eastwards again, Schott (1929), in view of the fact that hydrographic conditions in the western part of the Gulf of Aden were thought to be similar to those in the Straits of Gibraltar, constructed a section extending from the southern end of the Red Sea to the longitude of Aden, showing the vertical distribution of temperature and salinity, as based on the observations of the " Pola ", "Amiraglio Magnaghi" and " Ormonde ". This section did not suggest at all that the deep current from the Red Sea bends upwards at the sill near Great Hanish Island and runs backwards into the Red Sea, as has been similarly suggested by Rafael de Buen to be happening in the Mediterranean, but, on the other hand, confirmed the outflow of a Red Sea deep current into the Gulf of Aden. Schott further pointed out that, in analogy with conditions in the Straits of Gibraltar, there is in the Gulf above this deep current, between 100 and 500 m. depths, a mass of water with low salinity which moves westwards with an axis at about 200 m. depth.

In his report on the observations of the " Ormonde ", Matthews (1927) pointed out that the deep water below 1750 m. on the bottom of the Gulf at the most eastern station of the " Ormonde " has a temperature and a salinity similar to those of the water found at the same depths in the open ocean.

Van Riel (1932), reporting on the observations made by the "Snellius" in the Gulf of Aden, stated that seasonal changes in the hydrographic conditions in the Gulf of Aden would occur with the change of the monsoons.

Sewell (1934), in his preliminary report on the temperature and halogen-content observations of the present Expedition, suggested that the circulation at the eastern end of the Gulf is complicated and found that conditions are reversed in the different cruises in autumn and spring.

Gulf of Oman.

This Gulf is in open communication with the shallow Persian Gulf through the Straits of Hormuz ; there is no submarine ridge between the two gulfs. With the exception of the description of the surface currents given by Schott (1918) very little was previously known about the hydrographic conditions in the Gulf of Oman. The temperature and

halogen-content observations of the present Expedition have suggested the efflux of a current from the Persian Gulf into the Gulf of Oman (Sewell, 1934).

The Circulation in the Depths of the Indian Ocean.

Our present-day knowledge of the hydrography of the Indian Ocean and its adjoining gulfs is derived mainly from the oceanographical observations of the "Challenger", "Gazelle", "Vitiaz", "Valdivia", "Gauss", "Planet", "Möwe", "Pola", "Sealark", "Investigator", "Amiraglio Magnaghi", "Ormonde", "Dana", "Snellius", "Mabahiss" and "Discovery II", and from other observations taken mostly by the surveying ships of the British Admiralty.

The first important contribution to our knowledge of the circulation of the Indian Ocean was furnished by the results of the "Gauss". In discussing the observations of the "Gauss" along a number of sections which extended northwards from the Antarctic across the southern Indian Ocean, Drygalski (1926) put forward evidence to show that in the southern Indian Ocean the water is stratified and that four water masses can be recognized, namely, the surface water, the polar water, the tropical water and the bottom water. According to Drygalski the surface layer can be traced from the south polar region as far north as lat. 55° S. Beneath this surface layer lies the polar water, which originates from the Antarctic and then moves in a north direction. North of lat. 50° S. it submerges and then flows at a depth of about 1000 m. to beyond the equator. Beneath the polar water is the tropical water which, because its temperature is higher than that of the water above and below it at the edge of the Antarctic shelf, and its salinity is also higher, Drygalski assumed to have originated in warmer seas in the north and to be flowing southwards. Finally the cold bottom water lies beneath the tropical water; this bottom water fills the bottom of the ocean to beyond the equator According to Drygalski this bottom water is formed from a mixture of tropical and polar waters, but its mass is mainly derived from the tropical water, because this is quantitatively greater at the shelf edge than the polar water and its salinity is exactly or almost exactly the same as that of the bottom water. Drygalski assumed that the tropical water is cooled at the edge of the continental shelf through its contact with the polar water—occasionally also through climatic influences—and that it therefore becomes heavier and sinks to the bottom

After the "Gauss" observations were published, Schott (1926) drew a meridional salinity section along long. 60° E. from Kaiser-Wilhelm Land to Socotra (from 66° S. to 10° N. lat.) which he based on the "Gauss" observations as well as on other available data. His section confirmed the fundamental pattern of the circulation in the Indian Ocean as put forward by Drygalski. Schott further emphasized the remarkable analogy between the stratification of the water masses and the deep circulation in the southern Indian Ocean and the Atlantic Ocean. This resemblance led Schott to the use of a nomenclature of the water strata analogous to that of the Atlantic Ocean. Besides the surface layer he distinguished the Antarctic intermediate current (Drygalski's polar water), the North Indian deep current (Drygalski's tropical water) and the Antarctic bottom water. He also indicated that the North Indian deep current is formed by the sinking of highly saline surface water from the Arabian Sea and adjoining gulfs.

In 1929 Dr. Lotte Möller published the results of a comprehensive investigation,

which was suggested and planned by A. Merz, into the circulation of the Indian Ocean. This investigation comprised the construction and description of four salinity and seven temperature sections. The construction of these sections was based on all available serial observations of temperature and salinity taken by various expeditions and ships during the period of northern winter—the north-east monsoon period. All these observations were reduced to modern standards and checked by means of the temperature-salinity correlation curves. This investigation included also the construction and description of twelve stream-lined monthly surface current charts for the area of the ocean north of lat. 20° S. The construction of these charts was based on the German, British and Dutch atlases of the currents of the Indian Ocean, as well as on the works of Michaelis (1923) and Töpelmann (1922).

From her discussion of the vertical distribution of temperature and salinity along the various sections, Möller gave a picture of the nature of the circulation in the Indian Ocean, showing the existence of four layers of water superimposed upon one another. The description, sources of origin and movement of these water strata can be summarized as follows :

(1) A warm upper layer, including the surface water, with high temperatures and salinities, known as the sub-tropical layer, and which is generally a few hundred metres thick.

(2) The Antarctic intermediate layer, composed of cooler and less saline water of Antarctic origin. This layer is formed by the sinking of cold Antarctic surface water under the warmer sub-tropical water in the region of the sub-polar convergence between lat. 40° and 50° S. This water then flows northwards, with an axis at about 1200 m. ; its course is not due north but is north-west at first and then north-east. At the end of its journey it rises and mixes with the water that feeds the North Indian deep current.

(3) The North Indian deep current—a mid-water layer, warm and with a high salinity. It is formed in the Arabian Sea and the north-western part of the Indian Ocean. Here there is great evaporation and the surface water of this part of the ocean, which consists of a mixture of sub-tropical and Antarctic intermediate waters, becomes denser, sinks downwards and flows southwards as the North Indian deep current. The outflow of water of high salinity from the middle depths of the Red Sea and the Persian Gulf into the Arabian Sea promotes the formation of this current. According to Möller this North Indian deep current flows south and traverses the whole ocean to lat. 60° S. beneath the Antarctic intermediate current. Near the south polar continent it rises, mixes with the thaw water along the edge of the land and then sinks again as the bottom current.

(4) The Antarctic bottom water, comprising cold water of Antarctic origin with low salinity, creeps northwards under the North Indian deep current, losing its characteristics on the way, so that near the equator it can scarcely be distinguished from the water above it. Its movement is dependent on the contour of the bed of the ocean.

Such is the picture of the circulation of the Indian Ocean as brought forward by the investigation of Möller. In its general features the picture still remains undisputed, though some of its details have been recently either questioned or elaborated.

On the basis of all available sources of bottom temperatures, Sewell (1932) constructed

a chart showing the probable course of the Antarctic bottom water from the south polar regions through the Indian Ocean to the north. The chart shows that the Antarctic bottom water drifts northwards in three main tongues, of which the eastern one can be traced into the Bay of Bengal, the second drifts into the Arabian Sea between the Chagos Archipelago and the Seychelles and the third or most westerly appears to end east of Madagascar.

Using the observations made by the " Dana " in 1929–1930, and by the " Snellius " in 1929, in the tropical and sub-tropical parts of the Indian Ocean, Thomsen (1933) showed that the North Indian deep current did not carry water with a salinity greater than 34·80 per mille south of a line from the northern end of Madagascar to Ceylon. He concluded, therefore, that Möller's assumption that the highly saline deep layer in the south was a continuation of the North Indian deep current could not be justified.

Möller (1933) disagreed with Thomsen and did not find in the new observations of the " Dana " and the " Snellius " enough justification for modifying her conclusions with regard to the North Indian deep current, and regarded the existing data as sufficient to show that this current flows southwards as far as the Antarctic regions and that the failure of the " Dana " and " Snellius " observations to indicate the existence of this current is probably due to great fluctuations in its salinity owing to similar variations in the salinity of the coastal waters.

New light was thrown on this controversial question by the observations of R.R.S. " Discovery II " in 1935. On her voyage from the Antarctic the " Discovery II " made a series of stations on a line from Marion Island through the Mozambique Channel to the Gulf of Aden. A preliminary examination of these observations by Clowes and Deacon (1935) showed that although the North Indian deep current could be detected (from its high salinity of 34·80 $^{\circ}/_{\circ\circ}$) as far as 20° S., the highly saline water found in the south-western part of the ocean as far north as 50° S. is not its continuation. The temperature and oxygen content of this latter water suggested that it belonged to an eastward movement of the Atlantic deep current, as was suggested by Merz and Wüst (1922). Further, the oyxgen distribution along the " Discovery II " section suggested that the North Indian deep current did not come to a sudden termination at latitude 20° S. and indicated that it can be traced much further south as a tongue of poorly oxygenated water sandwiched between Antarctic intermediate water and an eastward current of Atlantic deep water. Clowes and Deacon also suggested that the volume and salinity of the north Indian deep current might be subject to large variations, probably related to the change of salinity in the coastal regions and to the current differences brought about by the changes of the monsoon winds and variation in the south equatorial current.

Wüst (1935) came to the same conclusion as that reached by Clowes and Deacon regarding the Atlantic origin of the high salinity deep water in the south-western Indian Ocean.

Later, Thomsen (1935) made a further study of the " Dana " and " Snellius " observations by constructing temperature-salinity correlation curves. From his analysis of these curves Thomsen showed that in the Indian Ocean there can be distinguished seven water strata. He pointed out once more that the North Indian deep current was not found to flow at a depth of 2000–3000 m. south of a line between Ceylon and Cape Delgado, but that it is possible that a rudimentary, southerly-directed current, with a nucleus at about 1200 m., exists south of this line. Thomsen also reached the conclusion that the bottom water in the

Indian Ocean results from mixing between the Antarctic bottom water and the eastward drift of the Atlantic deep water. He also pointed out that the Antarctic intermediate current mixes on its way northwards with the over- and underlying waters, and that it rises nearer to the surface as it advances north. With regard to the fate of the water carried north by this current and also by the bottom current, Thomsen stated that it is not improbable that this water wells up to the surface and mixes slowly with the surface water to serve as a compensation for the loss due to evaporation in the northern regions.

Having briefly reviewed our present-day knowledge of the deep circulation in the north-western Indian Ocean and its adjoining gulfs, we are now in a position to discuss the significance of, and to draw some conclusions from, the distribution of pH.

Conclusions.

The pH-Depth Curve.

The long-held view, first put forward by Palitzsch (1912), that the pH decreases continually with increase of depth in the sea is now known to be incorrect, and should be abandoned in view of the modern precision of pH measurement and the application of the corrections which this measurement involves.

The pH of any water mass is determined by its carbonic-acid equilibrium, which not only depends on its origin, but is influenced to varying degrees in the upper levels by planktonic activity, in the great depths by oxidation and geochemical processes and at the boundaries where it meets other water bodies by mixing. It is, therefore, evident that the shape of the pH-depth curve in any oceanic region is determined by the pH of the various water masses constituting the sampled water column.

Gaarder (1927) found that the pH-depth curve in the north-eastern Atlantic exhibits a peak below the surface due to a maximum of phytoplanktonic activity. Seiwell (1931) showed that the pH-depth curve in the north Atlantic exhibits an increase of pH near the bottom when the pH values are corrected for temperature. The " Meteor " observations in the South Atlantic provided abundant evidence to disprove Palitzsch's view (Wattenberg, 1933). Our pH observations in the north-western Indian Ocean and its adjoining gulfs provide similar new evidence, which is partly seen at a glance from Text-fig. 2, where several pH-depth curves are represented.

Water Movements Through the Straits of Bab-el-Mandeb.

The winter monsoon period.—Our observations of pH in May, at the end of the winter monsoon period, confirm the conclusions already arrived at by the direct measurements of H.M.S. " Stork " in January (Gedge, 1898), and by the " Amiraglio Magnaghi " in March–April (Vercelli, 1925), with regard to the water movements in the Straits of Bab-el-Mandeb.

During the winter monsoon period there pass northwards through the Straits of Bab-el-Mandeb a surface current from the Gulf of Aden and a deep current in the opposite direction out of the Red Sea. According to the " Stork " measurements (January) the separating boundary between these two currents lay at about 137 m.; according to the " Amiraglio Magnaghi " measurements (March–April) it lay at about 100 m.; and according to our observations it lay at a depth of about 50 m. It seems, therefore, that the volume of the surface current gets less and less as the winter season approaches its end.

With regard to the water exchange through the Straits during the winter monsoon period, our pH observations bring to light the fact that the bottom Red Sea water is not

involved to any great extent in the water exchange, and that the outflowing current consists almost entirely of mid and deep Red Sea waters. This is the reason why we have spoken of the outflowing current during this period as the Red Sea *deep* current.

The summer monsoon period.—Observations of pH at the end of the summer season lead to conclusions with regard to the water movements through the Straits of Bab-el-Mandeb which agree very well with the direct measurements made by the " Amiraglio Magnaghi " in July (Vercelli, 1931).

During the summer monsoon period there pass through the Straits of Bab-el-Mandeb three currents, of which the middle one, which constitutes the bulk of the water column in the Straits, flows from the Gulf of Aden into the Red Sea with a nucleus at about 80 m. The upper and bottom currents flow out of the Red Sea into the Gulf of Aden.

The above summary constitutes the facts of the *régime* of currents through the Straits of Bab-el-Mandeb during the two monsoon seasons. When we seek an explanation of these seasonal changes in the currents we find that the following factors have to be taken into consideration :

(1) The seasonal changes of the monsoons ; during the north-east monsoon period the prevailing wind in the southern part of the Red Sea is S.S.E., whereas it is N.N.W. during the south-west monsoon period.

(2) The seasonal variation in the sea-level in the Red Sea as a whole ; according to the Admiralty Tide Tables, Part II, the sea-level is relatively lower at Suez than it is at Perim during the summer months, whereas it is relatively higher at Suez than at Perim during the winter months.

(3) The difference in density of the waters in the Red Sea and in the Gulf of Aden which gives rise to a gradient current.

(4) The alternating periodic motion of tidal currents through the Straits.

Disregarding the effect of the tidal currents, we should expect, in the light of the above facts, both from density-gradient and wind-effect points of view, a surface current (the resultant of wind-effect and density gradient) to flow from the Gulf of Aden into the Red Sea during the winter monsoon period. This we have found to be actually the case, and, in compensation, a deep current flows out of the Red Sea. The balance between the inflow on the one hand and the outflow plus water loss by evaporation on the other seems, however, to be unattained in this season, and as a result water accumulates in the Red Sea and a general rise in the sea-level above the mean sea-level takes place.

Disregarding again the influence of the tidal currents, we find that in the summer months, under the dominating influence of the wind, a surface current flows out of the Red Sea into the Gulf of Aden.

Hence we come to a very important conclusion, namely, that the *régime* of currents through the Straits of Bab-el-Mandeb is determined mainly by the seasonal change in the winds and that other factors are of secondary importance in this respect.

It seems, again, that during the summer months the balance is not attained, the water loss by evaporation from the Red Sea plus the outflow into the Gulf of Aden being in excess of the inflow from the Gulf of Aden. Hence we get a general lowering of the sea-level below the mean sea-level in the Red Sea.

In presenting the above arguments we have disregarded the influence of the tidal streams, since it is evident that these streams would influence the speed of the wind-driven current only periodically. To what depth this influence extends and whether it reverses

at times the direction of the wind-driven current are questions on which our observations cannot throw any light.

The Water Masses in the Gulf of Aden.

A general scheme of the circulation in the Gulf of Aden has not yet been formulated. Here we shall confine ourselves to a description of the various water masses in the Gulf as revealed by our pH observations. This may contribute towards the formulation of such a scheme.

Conditions in May.—From a pH standpoint we can distinguish in the Gulf of Aden during May four water strata :

(1) The surface layer, which varies in thickness from 50 to 100 m., has a westerly movement under the influence of the prevailing wind.

(2) Below the surface layer is a sub-surface stratum, characterized by low pH values, which extends down to a depth of 400 m., and has an axis at a depth of about 200 m. At the western end of the Gulf the thickness of this stratum gets smaller. Observations along Section E have suggested that this layer might be an offshoot of the Antarctic intermediate current, but this suggestion cannot be much emphasized owing to the limited number of observational stations at the eastern end of the Gulf.

(3) Beneath this sub-surface layer is the outflowing Red Sea deep current, characterized by relatively high pH values. This current has an axis at a depth of 600–800 m. in the west and at 800–1000 m. eastwards.

(4) Finally, there is the bottom water of the Gulf. Observations along Section E indicated the possibility of this water originating in the Indian Ocean south of the Socotra-Guardafui ridge, but it has not been possible to trace it any further in the open ocean.

Conditions in September–October.—Although the observations made in September came at the time of the change of the monsoons and those made in October came at the beginning of the winter season and, therefore, fell with those made in May in the one and the same season, these observations reflect, nevertheless, the relics of the summer conditions.

With the exception of the eastern part of the Gulf, where conditions appeared somewhat complicated during September–October, we find in the greater part of the Gulf the fourfold arrangement of water strata. The thickness of the various strata and their pH values are somewhat different during these months.

The surface layer is less thick and is sharply separated by well-pronounced pH gradients from the layer below it, which we have seen to move in the opposite direction towards the Red Sea as a compensating current. Beneath this layer is the water mass representing the outflowing Red Sea bottom current ; its volume is smaller and its pH is higher than in May. Finally, there is the bottom water of the Gulf, the volume of which is larger in these months.

The above conclusions with regard to the differentiation of the water masses in the Gulf of Aden agree fairly well with deductions made by other investigators. The westward movement of a sub-surface water mass between 100 and 500 m. with an axis at about 200 m. has been suggested by Schott (1929) from his discussion of the " Amiraglio Magnaghi " and " Ormonde" observations as has been already pointed out. The flow of the deep Red

Sea water eastwards into the Gulf of Aden has been observed by various expeditions. And, finally, Matthews (1927) suggested that the bottom water in the Gulf of Aden is of oceanic character.

The Deep Circulation of the North-Western Indian Ocean.

The North Indian deep current.—Our description of the vertical and horizontal distributions of pH off the South Arabian coast, in the Gulf of Oman and off the coast of India have thrown new light on the principal sources of the so-called North Indian deep current. As we have already seen from the review of our present-day knowledge of the deep circulation of the Indian Ocean, Schott and Möller made the assumption that this current is formed in the Arabian Sea, where, owing to evaporation, the surface water becomes denser, sinks downwards and then flows southwards. The properties of this current, high temperatures and salinities and low oxygen-content, are well-known (Clowes and Deacon, 1935). Since an examination of the oxygen data of the present Expedition shows that the minimum pH layer in these coastal regions of the Arabian Sea is also poorly oxygenated and that the reduction in oxygen-content within this layer stands in close relationship to the decrease in pH, it is self-evident that the minimum pH layer in these regions is the North Indian deep current itself.

In our description of the vertical distribution of pH we have established again and again the following characteristics of the minimum pH layer in these coastal regions :

(1) Firstly, it lies immediately below the surface layer and is separated from it by well-pronounced vertical pH gradients.

(2) Secondly, it attains a great thickness in these regions and possesses relatively low pH values.

(3) Finally, its upper boundary shows a closer approach to the surface than it does anywhere else in the north-western area of the Indian Ocean.

To account for these characteristics of the minimum pH layer it is necessary to consider a number of physical, chemical and biological conditions of the waters of these regions.

(1) Owing to the prevailing high surface temperatures of these waters in the winter months, evaporation renders the surface water denser and causes it to sink and lose contact with the atmosphere. The particles of such water sinking from the surface will obviously carry with them any oxygen which they contain.

(2) In spite of the fact that our observations in these coastal regions were made when the winter season had already begun, an examination of the temperature observations reveals, nevertheless, the presence of a distinct temperature gradient in the upper levels not far from the surface. This gradient was found to be more marked at the end of the summer season off the Arabian coast in the Gulf of Aden, where a drop of about 12° C. in temperature occurred between the surface and the depth of 50 m. It is probable that similar gradients occur in the summer in these coastal regions of the Arabian Sea as well. The development below the surface of a layer with a maximum temperature gradient (the so-called thermocline or discontinuity layer) during the summer gives rise to marked density gradients, notwithstanding the increase of surface salinity due to evaporation. Such a state of stability hinders mixing across the discontinuity boundary, so that the underlying water receives little or no oxygen from above. Its oxygen-content is gradually exhausted by processes of organic oxidations, the accumulation of

carbon dioxide being revealed by the low pH values. The development of a marked density gradient near the surface would also cause the decomposition of sinking organic matter (of similar specific gravity) to occur at a higher horizontal level than in regions where such a gradient is less marked or absent (Seiwell, 1934), a feature which results in an increase in the thickness of the minimum pH layer. A third possible effect of this sharp transition in temperature might be the death which it inflicts on planktonic organisms which happen to come in the sphere of influence of the transitional zone. On the whole, such decomposition processes which take place in the immediate neighbourhood of the surface should give rise to distinct vertical pH gradients.

(3) These processes of organic oxidations are further promoted by two other factors, namely, the relatively high temperatures within the minimum pH layer, which make possible a higher rate of oxidation, and the availability of organic matter. With regard to the latter factor, the work of Gilson (1937) on the nitrogen cycle in these waters clearly indicates that such coastal regions are much richer in plankton than the open ocean. The high surface values of pH observed in these regions also suggest a higher activity of the phytoplankton than in the open ocean. The sinking of this plentiful plankton after death would supply organic matter in abundance for the maintenance of organic oxidations.

It is thus seen that whereas the origin of the North Indian deep current is connected with the strong evaporation during the winter in the coastal regions of the Arabian Sea, the properties of low pH and low oxygen-content, which characterize this water mass and indicate its source, are due to intense organic oxidations taking place in these coastal regions on account of the development of a sharp thermocline in the summer. It is noteworthy that the zone between the depths of 83–102 m. and 1253–1536 m., in which there is a complete absence of life, a fact revealed by the present Expedition's trawling and dredging (Sewell, 1934), corresponds remarkably well with the limits of the minimum pH layer.

It is on account of the low pH character of the North Indian deep current that it has been possible to trace its movement and to define its position in the water column. Off the South Arabian and Indian coasts it lies immediately below the surface layer, but further west it is separated from it by the upper Antarctic intermediate current; off the African coast it is practically non-existent. The description of the horizontal distribution of pH has shown that this current, which exhibits a threefold division in the upper levels, tends to move south-westwards on account of the deviating force of the earth's rotation and that it sinks to greater depths on its way south until it reaches its greatest expanse at a depth of 800 m.* Moreover, the horizontal distribution of pH suggests, though the pH observations did not extend much south of the equator, that there is a tendency for this current to lose its distinctive character farther south.

Although the observations in the eastern approaches of the Gulf of Aden are too far apart to enable any precise statement to be made regarding the part played by the Red Sea water in the formation of this current, the author is inclined to suggest that the

* The suggestion made by Sewell (1934) with regard to the continuation of the North Indian deep current at a depth of 2500 m. in the position of Station 166 is unjustified, since the relatively high value of halogen-content (19·50‰) assumed to occur at this depth has been found, from a consideration of the depth of sampling as measured by the thermometric method, to be misleading.

principal sources of the North Indian deep current are confined to the South Arabian and north-western Indian coastal regions, and that on the basis of pH observations the Red Sea water does not seem to contribute any significant proportion to the formation of the North Indian deep current. There is, therefore, no justification in giving the Red Sea water such a prominence in the characterization of the water masses in the Indian Ocean as was done by Thomsen (1935).

The Antarctic intermediate current.—The water, characterized by pH values intermediate between the high values of the surface layer and the low values of the minimum pH layer, has been assumed to correspond with the Antarctic intermediate current. This current originates in the Antarctic regions and approaches the area under consideration from the south.

In the eastern regions of the area investigated this current lies below the North Indian deep current. In the central and western regions it is split up by the North Indian deep current into two portions, which we have designated as the upper and lower Antarctic intermediate currents; in these regions the upper Antarctic intermediate current lies below the surface layer and above the North Indian deep current. Off the African coast the Antarctic intermediate current shows no splitting owing to the absence of the North Indian deep current.

The horizontal distribution of pH has shown that the Antarctic intermediate current enters the area of the north-western Indian Ocean mainly on the western side. It tends then to move north-eastwards on account of the deflective force of the earth's rotation, rising nearer to the surface on its way north. In the position of Station 40 the upper Antarctic intermediate current divides into an easterly and a westerly branch, the latter moving towards the Gulf of Aden. It is suggested that this upper Antarctic intermediate current, with its possible rich stores of nutrient salts, is responsible for the higher activity of plankton and its outburst in the coastal regions of the Arabian Sea

The lower Antarctic intermediate current spreads widely at a depth of 2000 m. and reaches as far north as the Gulf of Oman. Indications of upwelling of this current in the central regions of the Arabian Sea have been shown by the vertical distribution. Both the upper and lower Antarctic intermediate currents show at certain levels a threefold division complementary to that of the North Indian deep current.

The Antarctic bottom current.—The depths of the north-western Indian Ocean below 3000 m. are filled with the Antarctic bottom water, which originates in the Antarctic regions and drifts northwards. On account of the topographical obstruction imposed by the Carlsberg and the Seychelles ridges, this water enters the area under consideration in three streams, the eastern one entering between Addu Atoll and the Chagos Archipelago, the central one between the Chagos Archipelago and the Seychelles, and the western one west of the Seychelles.

It is suggested that the exceptionally high pH values shown by this water, especially in the Arabian basin on the north-east side of the Carlsberg Ridge, are possibly due to local interaction with the floor of the ocean.

It is thus seen that the above conclusions throw further light on the origin, character and movement of the water masses in the north-western Indian Ocean and agree in some degree with the deductions made by other investigators. These conclusions should prove of some aid to the understanding of the distribution of life and its conditions in the area investigated.

We now turn to the consideration of certain biological and geochemical aspects of the pH distributions. The importance and usefulness of pH observations in these fields of study have been brought forward in a comprehensive review by Labbé (1932).

The Activity of the Phytoplankton.

A survey of the present state of our knowledge of the physical and chemical factors governing the production of phytoplankton in the sea is given by Gran (1932), and recently by Gilson (1937). The conditions for the production of phytoplankton in the north-western Indian Ocean as revealed by the nitrate and nitrite distributions in conjunction with the oxygen, stability, transparency and phytoplankton data of the present Expedition have been discussed in detail elsewhere in this volume by H. C. Gilson (1937). We shall confine ourselves here to summing up, in the light of our knowledge of the oceanic circulation deduced above, a few conclusions regarding the activity of the phytoplankton as brought about by our pH observations in the same area.

From the description of pH distributions we have seen that the highest pH values of the surface waters are found in the north-eastern area of the Arabian Sea and off the African coast. These values have been considered to signify a higher photosynthetic activity which might be due either to an abundance of phytoplankton or to an increased rate of photosynthetic processes. The theory developed by Brandt (1899, 1902 and 1920), according to which the productivity of the sea is limited by the supply to the surface layers of the necessary nutrient salts, is generally accepted. Both the maintenance of a large phytoplanktonic population and the rapidity of photosynthetic processes would therefore necessitate, amongst other conditions, a sufficient supply of nutrient salts.

The view has been put forward that coastal waters are relatively more productive than the open ocean on account of the influx of nutrient salts from the land ; but doubts have been cast on the correct uses of this view by Gilson (1937) ; and such a source must be insignificant or practically lacking in the area under investigation. Another possible source of supply of these salts is the upwelling of deep water, the immediate effect of which is to reduce the surface temperature and salinity. Evidence of this phenomenon exists for the African coast only (Matthews, 1926) ; observations of temperature and salinity at Station 22 of the present Expedition seem to give similar evidence.

In general, conditions off the African coast seem to favour the activity of the phytoplankton. Thus the Antarctic intermediate current, which rises towards the surface from greater depths as it moves north along this coast is bound to be rich in nutrient salts. On account of the instability of the upper part of the water column in this region this current mixes easily with the surface water and enriches it with nutrient salts. Moreover, the N.E. monsoon winds probably have the effect of carrying the plankton from the open ocean towards the African coast, and by far the richest phytoplankton of the whole area was found at Station 101 (Gilson, 1937, pp. 52 and 54).

In the north-eastern area of the Arabian Sea hydrographic conditions are different. Here, at any rate during the period of our observations, there is considerable stability in the upper part of the water column, which would hinder the supply of nutrient salts from the rich stores of the water below by mixing. Nutrient salts may be brought to the surface layer by eddy transfer, a mechanism suggested by Seiwell (1935), by which exchange of nutrient salts may be brought about in very stable waters, and regeneration

of nutrient salts within the surface layer itself is not altogether improbable ; but in any case this area appears to be an unproductive one.

Another aspect of pH distribution related to the activity of the phytoplankton is that the maximum pH value of the surface waters does not as a rule occur at the very surface of the sea, but just below it. This feature was well-pronounced in the months of September–October at stations in the Gulf of Aden and in the north-eastern area of the Arabian Sea. Such an increase in photosynthetic activity below the surface has been attributed to the possibility that the light is too intense at the surface during these months (*cf.* Gilson, 1937, pp. 38, 39).

Finally, light has been thrown on the depth of the photosynthetic layer in the Gulf of Aden and in the north-eastern region of the Arabian Sea, especially during the months of September and October. Temperature and pH observations in these regions have shown the simultaneous development of maximum vertical pH and temperature gradients in the upper part of the water column at the same levels, a fact which has suggested that the depth of the photosynthetic layer was limited by the thermocline at the time of observation. The correspondence between the depths at which distinct pH and temperature vertical gradients occurred was less perfect during the other months. It is therefore concluded that the depth of the layer of phytoplanktonic activity in the regions under consideration is limited in the summer by the thermocline. A similar conclusion was arrived at by Seiwell (1935) with regard to the depth of this layer in the tropical North Atlantic from a study of the vertical distribution of phosphate and oxygen in the upper part of the water column. In view of this result it is suggested that during the winter months, owing to the absence of distinct thermal gradients in the upper part of the water column, the depth of the layer of phytoplanktonic activity in the north-eastern regions of the Arabian Sea is limited by light.

The Geochemical Effect of the Antarctic Bottom Current.

In the Arabian Sea, especially in its north-eastern basin, the pH values of the deep water in the vicinity of the bottom were found to be relatively high. It has been suggested that these high values are due to the geochemical effect of the Antarctic bottom current on the floor of the ocean. It is generally admitted that, on account of its origin, the Antarctic bottom current possesses a high content of carbon dioxide. By its solvent action under great pressures on the carbonate constitutents of the ocean floor the water acquires a higher pH and the carbonate-content of the sediments decreases.

The character of the sediments, obtained by the present Expedition from Stations 166 and 167, which indicates a poor content of carbonate, strengthens this view. A process of re-solution of calcareous sediments from the floor of the Arabian Sea is therefore presumably taking place at its greatest depths. Similar views on the relation between the poor carbonate content of the sediments and the Antarctic bottom current have been put forward by Wattenberg (1933) and Wüst (1934).

SUMMARY.

1. The pH observations made on the waters of all oceans and seas until 1934 are reviewed.

2. The details of a colorimetric method used by the John Murray Expedition for the

determination of the values of pH on board H.E.M.S. " Mabahiss " during her cruises in 1933–1934 are given and discussed.

3. The observations so obtained at 82 stations distributed over the area of the north-western Indian Ocean and its adjoining gulfs are reduced into such forms which make them comparable with other recent and old pH data given in the literature.

4. The vertical distribution of pH along thirteen sections and its horizontal distribution at thirteen levels in the area investigated are graphically illustrated and described.

5. Short-period variations of pH in certain regions of the area investigated are described and their bearing on the representativeness of our observations is discussed.

6. The distribution of pH is discussed and several conclusions regarding the origin, character and movement of water masses in the north-western Indian Ocean and its adjoining gulfs, the activity of the phytoplankton in the upper part of the water column and certain geochemical processes in the deeper water are deduced therefrom.

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APPENDIX

A NOTE ON THE DETERMINATION OF HYDROGEN SULPHIDE IN SEA-WATER WITHDRAWN FROM CERTAIN SAMPLES OF MUD COLLECTED FROM THE NORTH-WESTERN INDIAN OCEAN.

Introduction.

The discovery by the John Murray Expedition of an area in the Arabian Sea in which there was a complete absence of life has been of wide interest. Throughout this area the bottom consisted of a soft green mud, that in the neighbourhood of Ras el Hadd smelt strongly of hydrogen sulphide. Mud samples obtained from the lagoons of Addu, Fadiffolu and Horsburgh Maldive atolls were also found to be impregnated with this gas in varying degrees. A slight trace of it was detected in a bottom deposit of green mud obtained at Station 189 off the Arabian coast in the Gulf of Aden. On this discovery I was called on to determine the hydrogen sulphide content of the water occluded in these mud samples.

Method.

In view of the fact that no special chemical equipment was brought on board the "Mabahiss" to meet such an unexpected analysis, a method which is simple, rapid and convenient for use on board ship was employed. The analysis figures obtained by this method and recorded in this note do not claim any absolute significance. Defects which will be indicated in the course of this note, both in the technique employed in withdrawing the water from the mud and in the accuracy of the analytical method itself, make such an absolute significance remote. Nevertheless, the determinations were carried out with the purpose in view of exploratory quantitative study and of possible comparison with existing data from other dead regions.

With the exception of one sample, all the water samples were withdrawn from the mud by aspiration—a procedure which results in loss of gas and reduces therefore the H_2S content of the water aspirated off. This result is illustrated by the difference in the figures of analysis of three samples of water withdrawn from the same sample of mud (sample from Station 77) which are given in Table I.

Table I.

Water sample.	H_2S mg./l.
(*a*)	29·39
(*b*)	23·77
(*c*)	19·55

Sample (*a*) was obtained by simple filtration; samples (*b*) and (*c*) were aspirated off. Unfortunately this procedure of aspirating off the water from the mud had to be adopted because simple filtration was found to be extremely slow and gave water only in small quantities—insufficient for analytical purposes.

The method used for the determination of hydrogen sulphide consisted in adding a known excess of a standardized N/100 iodine solution in potassium iodide to a known volume of the water sample (100 c.c.) and titrating the iodine which was not reduced by hydrogen sulphide with sodium thiosulphate. The latter was standardized against iodate. Although the method, as already mentioned, is rapid and convenient for use on board ship, yet, as applied in sea-water analysis, it calls for analytical refinement, since its accuracy is limited by the interference of other reducing constituents of sea-water. Blank analysis carried out on H_2S-free water obtained from similar depths in the neighbouring regions suggests itself as a line of analytical refinement.

Results of Analysis.

In Table II are given the analysis figures of the H_2S content of the water aspirated off from the mud samples which are denoted by station numbers to be found in the List of Stations (Sewell, 1935), where data regarding position, date, etc. are given.

Table II.

Station.	Locality.	Sounding m.	Nature of bottom.	H_2S mg./litre.
77	Gulf of Oman, off Ras el Hadd	421	gn. m.	29·39*
137	Addu Atoll anchorage	46	w. m.	4·90
142A	Fadiffolu Atoll, E. side	31	br. and w. m.	3·92
142B	Fadiffolu Atoll, W. side	37	cm. m.	2·26
160	Horsburgh Atoll, N. side	37	,,	7·73
189	Gulf of Aden, off the Arabian coast	91	gn. s. m.	0·25

* Water sample obtained by simple filtration.

It is seen from these analysis figures that the highest H_2S content was found at Station 77 off Ras el Hadd where there seemed to be a complete absence of life, and this azoic condition must be related in some way or another to the presence of hydrogen sulphide in the mud. The lowest H_2S content was found in the Gulf of Aden, but in the lagoons of Addu, Fadiffolu and Horsburgh Atolls its content varies from 2·26 to 7·73 mg./litre. The absence of coral growth from the lagoons of Horsburgh Atoll and the scarcity of the bottom fauna in that of Addu Atoll were reported by Stanley Gardiner (1903), and it is sound enough to conclude with Sewell (1936) that the presence of this gas in the lagoons " may well prove to be distinctly adverse to the coral growth or to the existence of other forms of animal life ".

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